THE OPEN UNIVERSITY A SCIENCE FOUNDATION COURSE

UNITS 7–8 PLATE TECTONICS: A REVOLUTION IN THE EARTH SCIENCES

THE OPEN UNIVERSITY

THE SCIENCE FOUNDATION COURSE TEAM

The illustration on the front cover shows the fit of the continents along the continental slope at the 500-fathom contour line.

The Open University, Walton Hall, Milton Keynes, MK7 6AA.

First published 1988. Reprinted 1989, 1991, 1992, 1993, 1994.

Designed by the Graphic Design Group of the Open University.

Filmset by Santype International Limited, Salisbury, Wiltshire; printed by Henry Ling Ltd., at the Dorset Press, Dorchester, Dorset

ISBN 0 335 16328 9

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1.6

STUDY GUIDE

Units 7–8 cover one topic, the 20th-century revolution that has taken place in our understanding of the workings of the Earth's crust. The two Units have been written without a break because the subject matter does not divide conveniently into two discrete Units. Units 7–8 should take you two weeks to study; by the end of the first week you should have completed Sections 1 to 4.3, including the AV sequence 'Crustal patterns'.

Before you start work on Units 7–8, it is essential that you are thoroughly familiar with the terms and concepts introduced in the AV sequence 'Rocks and rock textures', which is associated with Units 5–6. You should have studied this material when completing those Units, but you may feel the need to revise it briefly now.

While studying Units 7–8 it will help if you can consult the World Ocean Floor map with ease, and not have to keep unfolding it. Use of this map is essential when reading Section 2.3 'Earth patterns'. Please take care not to mark the map, since it must be returned with the Kit.

Once you have finished Section 2 of these Units, you should study the AV sequence, 'Crustal patterns', because it gives the answers and provides follow-up discussion to a series of questions posed in Section 2. Note that answers to these are *not* given in this text, although you can check your understanding of the material by completing SAQs 1–5. The visual component of this sequence consists of the World Ocean Floor map from the Experiment Kit and Figures 7–11, which fold out from the back of this text.

There are no experiments associated with Units 7–8. The first of the two TV programmes deals with continental drift and plate tectonics, and the second with the nature of constructive margins. The second tape sequence comes at the end of the Units, and in it historical aspects of the initial rejection and final acceptance of the theory of plate tectonics are discussed.

You will find that many of the illustrations in these Units are accompanied by fairly long captions. Generally, these illustrations and captions are used to give a comprehensive description of, say, a feature of the Earth's surface or a particular scientific concept. The text discusses the significance of such features and concepts, and relates them to the historical development of aspects of the Earth sciences over the past 60 years. So the 'story' that provides the framework for Units 7–8 lies in the text, but most of the items you will want to concentrate on when revising are covered by the illustrations.

TECTONICS

1 INTRODUCTION

In earlier Units we examined how a number of simple observations concerning the properties of the Earth can be incorporated into *models* of its internal structure and composition. The scale of the models discussed in Units 5–6 is so vast that it is almost beyond the scope of human imagination. In Units 7–8 we shall continue to make basic observations about our planet, but we shall now examine the nature of the Earth's outer skin, the crust, and its familiar surface expression, the continents and oceans. In addition to discussing observations, hypotheses and models, we shall explain how ideas concerning the workings of the crust have changed over the past 75 years, not just because this is a fascinating story, but also because it illustrates science as a human activity and shows how scientific advances are often related to social, political and technological developments.

In Section 2 you will study the Earth's surface features using a number of maps printed with the text, and the large World Ocean Floor map that accompanies these Units. This will lead to a discussion of the major vertical and horizontal variations in the composition and structure of the crust. When you have finished Section 2, you should be able to *describe the major features of the Earth's crust and its surface.*

In Section 3 we shall examine how ideas concerning the origin of continents and oceans have changed over the past 75 years, and in Section 4 we will show how the phenomena discussed in Section 2 are explained today by the theory known as 'plate tectonics'. **'Tectonics'** is about movements of the Earth's crust, particularly on a large scale, and the resulting structures. When you have finished Sections 3 and 4, you should be able to *describe the theory of plate tectonics* and summarize the evidence and lines of reasoning that underpin it. A synthesis of the geological implications of plate tectonics is given in Section 5.

Once you have been introduced to plate tectonics, you may be surprised that despite a considerable amount of supporting evidence, the idea of continental drift was not accepted 75 years ago. But, as you will see when you study the detailed story concerning this revolution in the Earth sciences, progress in science does not happen in a vacuum. It is intimately linked not only to developments in other scientific disciplines, but also to technological and political events. In this respect, there is nothing unique about the history of plate tectonics, for advances in other fields which you will meet during the Course were also linked to contemporary events—and some of these may also be termed 'scientific revolutions'. So, when you have completed Sections 3 and 6 you should *understand how the development of the plate tectonic theory was influenced by technological and political developments, and why we can consider it to be a scientific revolution.*

2 CRUSTAL PATTERNS

Allow about one hour for a first read through Sections 2.1 to 2.4. The associated AV sequence 'Crustal patterns' will take about 45 minutes.

2.1 WHY ARE THERE CONTINENTS?

In Units 5–6, evidence was presented that supported a multi-shelled model for the internal structure of the Earth. The Earth's core is divided into inner and outer parts, and outside the core there are further concentric shells of mantle and crust. You might expect this concentric pattern to continue into the detailed structure of the Earth's outer skin. But this skin, though consisting of gabbroic and granitic material, which is covered by the oceans and gaseous atmosphere, does not show a regular layered structure (Figure 1). We find that the less dense granitic material is dotted about the Earth's surface in slabs of irregular thickness with water occupying the hollows in between, instead of being spread uniformly over the globe as a single, shoreless ocean. (If all the water in the present-day oceans were spread uniformly over the Earth as depicted in Figure 1b, the single, shoreless ocean would be 2.6 km deep.) This irregular distribution of crustal materials implies that something must have separated the lighter continental crust into slabs at some stage during the Earth's history.

We know that continents were formed very early during the Earth's history. As you will see in Units 28–29, the Earth is considered to have formed approximately 4 500 Ma (4.5×10^9 years) ago—a time-span that is almost impossible to imagine. The oldest rocks found on the continents have been dated at 3.8×10^9 years. So it seems that continental crust has existed for a vast period of time. The present volume of land above sea-level is about $13 \times 10^7\,\mathrm{km}^3$, and it is estimated that $13.6\,\mathrm{km}^3$ of rock material is removed from the land to the oceans every year by a process called erosion (Figure 2). If this were the only geological process operating on the continents, how long would they last? If the erosion continued at the same rate until they were planed flat, the continents would be covered by the sea in slightly less than ten million years—yet they have lasted thousands of millions of years (over two orders of magnitude longer than the estimate suggests). In reality, erosion would not continue at the same rate but would slow down because as irregularities in the surface (called the 'relief') of the continents were diminished, rivers would flow more slowly, and so carry less material. Nevertheless, if erosion continued—albeit at a diminishing rate—other processes must have operated to maintain the continents through the vast span of the Earth's history.

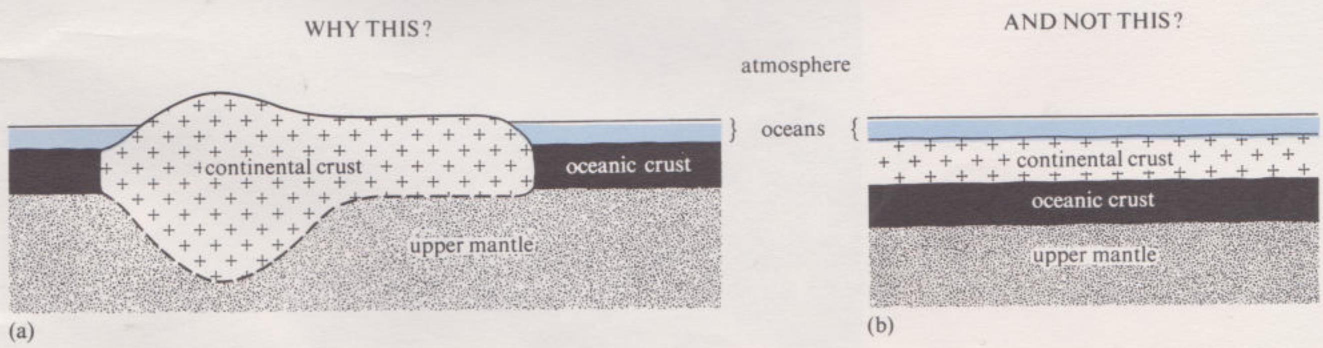


FIGURE 1 When the structure of the outer 'skin' of the Earth is examined, the idea of a model consisting of concentric shells breaks down. Instead of granitic and gabbroic crust and the overlying ocean forming successive shells of uniform thickness, the base of the crust mirrors, in an exaggerated way, the surface relief of the Earth (as you will see in Sections 3.4 and 4.4).

FIGURE 2 Vast amounts of material are removed from the continents by erosion and deposited in the oceans every year, yet most of the continental crust has remained above sea-level for thousands of millions of years. Processes operating to remove rock material from the continents to the ocean basins involve the interaction of air, water, temperature changes, and the effects of gravity. Heat from the Sun leads to evaporation of water from the oceans, which falls as rain or snow over land areas, whence it returns to oceans via lakes, rivers and underground flow.

(a)

(a) Masses of rock debris loosened by alternating freezing and thawing have accumulated beneath the steep valley side. Gravity has been responsible for their movement after initial loosening from the parent rock.

(b)

(b) Coastal erosion. The action of waves has resulted in the cliff line receding. Ribs of steeply inclined rock strata stand out above the beach sands. The sands are derived from the breakdown of solid rock.

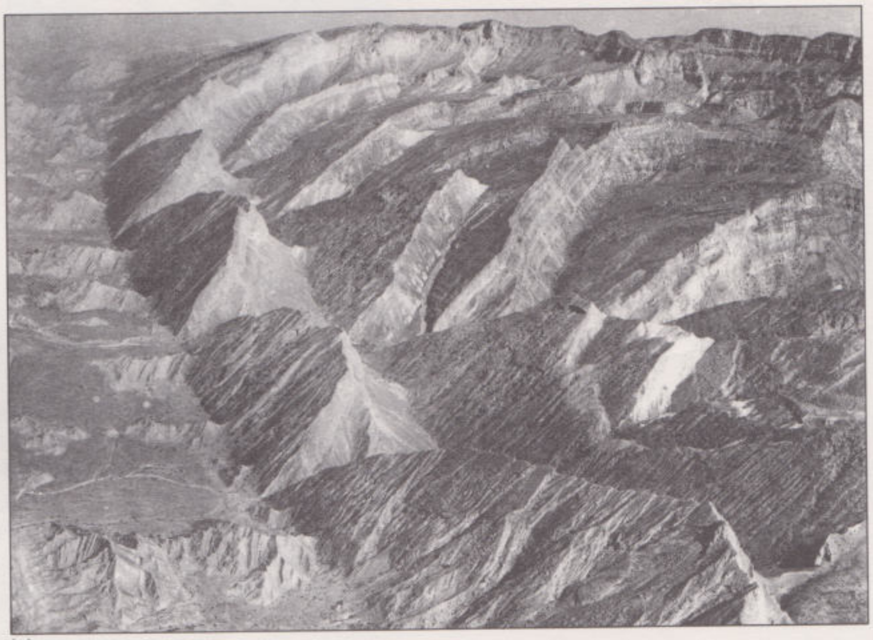
(c)

(c) Deposition of sands and muds in an estuary. Reduction in the speed of river currents as they reach the sea causes rock debris (that is, sand, silt and mud) to be deposited. In the future, if these deposits were to be buried, they would become 'new' sedimentary rocks.

The discussion in the previous two paragraphs provides a brief glimpse of the problems posed by the nature and distribution of the features of the Earth's solid surface. It is clear that processes have operated, and still are operating, to maintain the relief of the continental crust. This is in marked contrast to the situation on the Earth's nearest neighbour, the Moon (Figure 3). The lunar surface not only looks different from that of our home planet, but it is dominated by immensely old rocks—older than 3 000 Ma. The Moon's surface has altered little in this vast period since the rocks were formed, whereas the Earth's outer skin has been re-worked by geological processes time and time again so that over three-quarters of its surface is less than 200 Ma old. The processes that caused such re-working are the subject of these Units and much of Units 27 to 29.

To begin to understand some of these processes we must now examine in more detail the surface features of the solid Earth.

FIGURE 3 The ages and form of the surface features of the Earth and Moon are completely different, reflecting their different geological histories.



(a)

(a) A deeply eroded region of sedimentary rocks (about 100 Ma old) shows a layered structure that was originally horizontal but has been deformed by Earth movements.

(b)

(b) The Moon's surface is over 3 000 million years old, and suffered extensive cratering early in its history. These ancient features have been preserved because the Moon has not experienced crustal movements of the kind seen on the Earth, and also because there is no erosion by wind and water.

2.2 SURFACE FEATURES OF THE EARTH

2.2.1 HEIGHTS AND DEPTHS

At first sight there does not seem to be much order about the overall distributions of land and sea on our globe. But one hemisphere contains most of the land areas, and the other most of the ocean areas (Figure 4). Taken as a whole, the planet's surface is dominated by water, 71% of it being covered by seas.

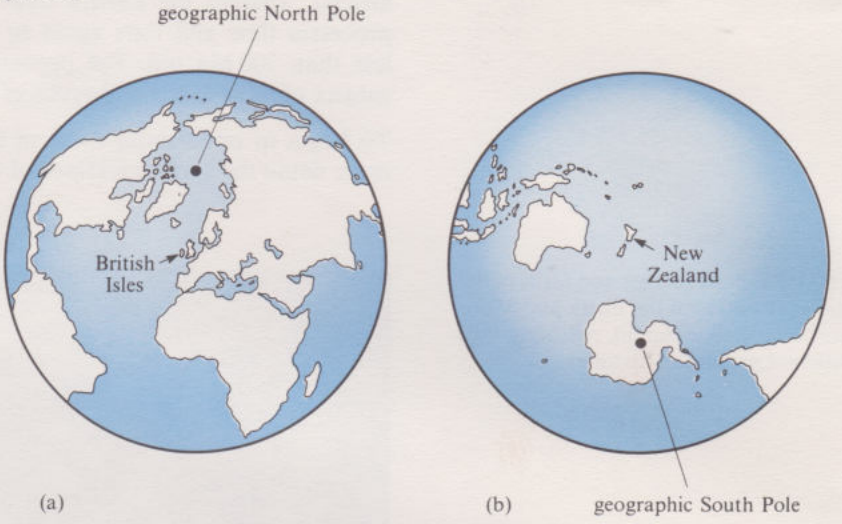


FIGURE 4 The Earth's 'continental' and oceanic hemispheres. The non-uniform distribution of continents is highlighted in these two views of the Earth, portrayed (a) from directly above the British Isles, and (b) from above New Zealand.

So the distribution of land and sea is not uniform over the Earth's surface. But what about the distribution of heights both above and below sea-level: what pattern would you expect these to show? The *simplest* distribution would be one in which the bulk of the Earth's solid surface lay just above or just below sea-level, with progressively less at higher altitudes and greater ocean depths. This is certainly the simplest pattern imaginable, but what is the distribution actually like? Table 1 gives the results of surface area measurements made on a map of the Earth showing land and submarine contours at one kilometre intervals both above and below sea-level. The second column of this Table shows that the simple pattern does not apply, for there is not just one 'peak', but two.

TABLE 1 The distribution by height and depth of the Earth's solid surface. The data show that the dominant heights and depths are not clustered around sea-level as might be expected, but that they occur as two distinct 'peaks'.

Height or depth interval/km	Percentage of total surface area of the Earth (total = $51 \times 10^7\,km^2$)	Cumulative percentage area*
Above sea-level		
5–9	0.1	0.1
4–5	0.4	0.5
3–4	1.1	1.6
2–3	2.2	3.8
1–2	4.5	8.3
0–1	**20.8**	29.1
Below sea-level		
0–1	8.4	37.5
1–2	3.1	40.6
2–3	6.1	46.7
3–4	14.7	61.4
4–5	**22.6**	84.0
5–6	15.0	99.0
6–7	0.9	99.9
7–12	0.1	100.0

* Cumulative area is found by successively adding the entries in the middle column. Thus the cumulative area at the 2–3 km interval is the total of the first four entries in the middle column; it means that 3.8% of the Earth's surface is higher than 2 km above sea-level. Similarly the first entry below sea-level means that 37.5% of the Earth's surface is higher than 1 km below sea-level.

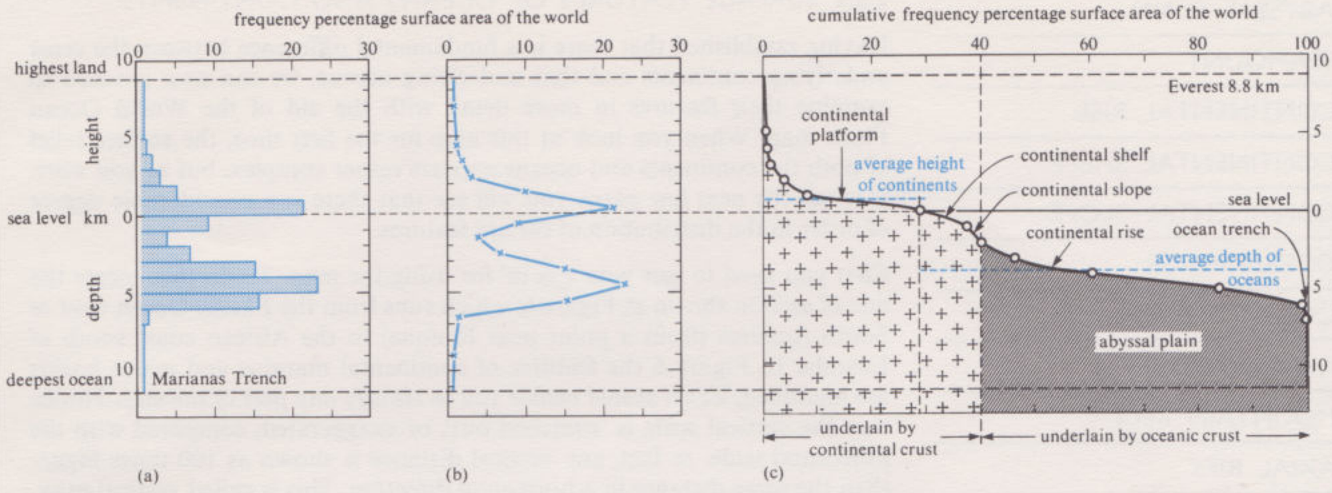


FIGURE 5 Three methods of graphically illustrating the distribution of the areas of the solid Earth's surface, using the data given in Table 1. All the methods show the two principal levels, one characteristic of the continents, the other of the oceans.

(a) A *histogram* or bar-chart in which the length of the bar is proportional to the percentage represented.

(b) A *frequency curve*, in which the percentages given in Table 1 are plotted as single points (for example, the value for the 1–2 km interval is plotted at its mid-point of 1.5 km, for the 2–3 km interval at 2.5 km, and so on) and the points are then joined. This method of plotting approximates much more closely to the true distribution, for clearly the Earth's relief is not made up of a series of steps as depicted in Figure 5a.

(c) A *cumulative frequency curve*, plotted in the same way as Figure 5b but using the data from the third column of Table 1.

Note The usual convention when constructing histograms, frequency curves and cumulative frequency curves is to plot percentages vertically, and not horizontally as in these examples. The reason for breaking the convention in this case is self-evident—especially for Figure 5c—but note this is not a *profile*, but a cumulative frequency curve. The similarity in shape to parts of Figure 6 is coincidental.

The distribution of areas of the Earth's surface at different altitudes is demonstrated with much more impact if the data in Table 1 are presented in graphical form, as shown in Figure 5. The graphs in this Figure leave no doubt that the solid Earth's surface is dominated by two principal ranges of levels, one characteristic of continental regions, the other of oceans. The range is considerably wider for the oceans (3–6 km deep) compared with the continents (0–1 km above sea-level).

□ Do you recall a fundamental difference between the nature of continental crust and that of oceanic crust?

■ Continental crust is less dense than oceanic crust (remember Table 7 in Section 4 of Units 5–6, which summarized the properties of the Earth's layers). So the two principal crustal levels shown in Figure 5 are underlain by material of different densities: gabbroic material (similar to specimen S5 in your Experiment Kit) under the oceans, and granitic material (specimen S1) forming much of the upper continental crust. This density contrast, combined with the surface shape, suggests a model in which the crust is floating on the mantle with the less dense continental material standing higher. This is analogous to blocks of wood of different densities but identical shapes being submerged to different depths when floating on water.

We shall return to the significance of this model later. For the moment it is sufficient to emphasize that for a geologist, the terms 'continental' and 'oceanic' have different meanings from the usual ones. 'Oceanic' for the non-specialist has connotations of water, but to the geologist the term is concerned with the part of the crust that has a density of $2\,800$–$3\,000\,\mathrm{kg\,m^{-3}}$, as opposed to a density of $2\,600$–$2\,800\,\mathrm{kg\,m^{-3}}$ for a granitic continental crust. It so happens that the oceans cover the boundary between oceanic and continental crust (Figure 5c); indeed, about 25% of continental crust is covered by the sea.

ABYSSAL PLAIN
SEAMOUNT
CONTINENTAL RISE
CONTINENTAL SHELF
CONTINENTAL SLOPE
OCEAN RIDGE
OCEAN TRENCH
ISLAND ARC
MOUNTAIN BELT
AXIAL RIFT

2.2.2 SURFACE FEATURES OF OCEANS AND CONTINENTS

Having established that there is a fundamental difference between the crust underlying continents and that underlying oceans, we can now proceed to examine their features in more detail with the aid of the World Ocean Floor map. When you look at this map for the first time, the surface relief of both the continents and oceans appears rather complex, but as you work through the next few pages you will see that there is a considerable degree of order in the distribution of certain features.

First you need to 'get your eye in' for using the map. To do this, locate the line of section shown in Figure 6, which runs from the Pacific Ocean west of South America (from a point near Iquique) to the African coast south of Luanda. In Figure 6 the features of continental margins and ocean basins are identified, *which should enable you to classify any part of the map.* Notice that the vertical scale is 'stretched out', or exaggerated, compared with the horizontal scale. In fact, any vertical distance is shown as 100 times bigger than the same distance in a horizontal direction. This is called vertical exaggeration; in this case it is ×100. You should always look carefully at profile diagrams of this kind to see if there is any exaggeration, because the effect of vertical exaggeration is to make the slopes look very much steeper than they really are. Compare the apparent slopes in Figure 6 with the values given below in the definitions of continental slope and rise.

Some of the features shown on Figure 6 need to be explained. The **abyssal plains** are those parts of the ocean floor that lie between 4 and 6 km below the surface. They have generally very low relief, with the exception of **seamounts**, which are isolated, more or less conical mountains. The abyssal plains make up the major part of the ocean floor.

The **continental rise** is the area of the ocean floor that marks the transition between the continental slopes and the abyssal plains. The average gradient of the continental rise is about half a degree, and it is several hundreds of kilometres wide. The **continental shelf** is the area of the ocean floor bordering the continental land masses at a depth of about 200 m below the sea surface, and it has an average slope of about a tenth of a degree. The **continental slope** is the area of the ocean floor extending from the edge of the continental shelf to the start of the continental rise. The slope has an average gradient of about four degrees.

The **ocean ridges** are the elongated 'mountainous' parts of the ocean floor. The **ocean trenches** are elongated troughs in the ocean floor, extending from the depth of the abyssal plains to the greatest depths of the oceans (just over 11 km). Where the trenches are located within ocean basins, they are bordered by chains of islands known as **island arcs**. Spend some time studying the World Ocean Floor map, and try to answer the following questions before reading on.

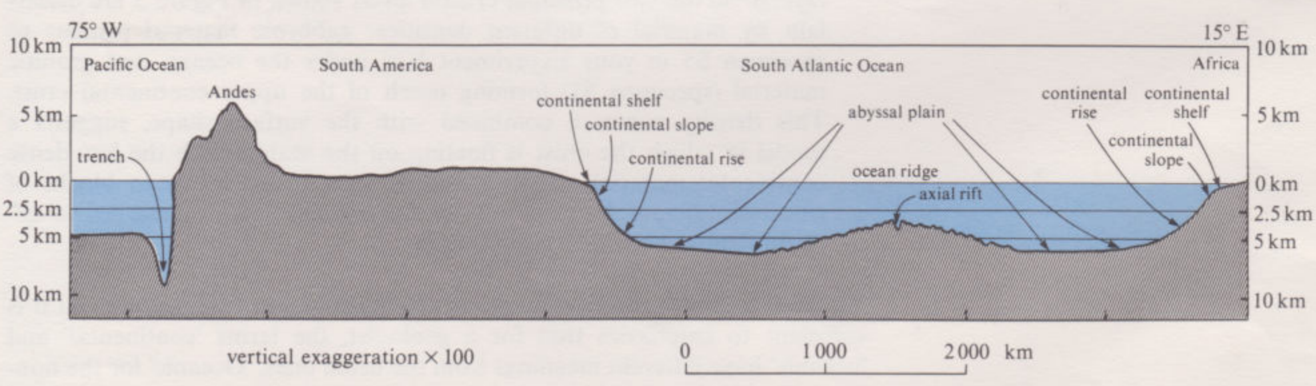


FIGURE 6 Cross-section to show the surface of the Earth's crust between South America and Africa. You should locate the line of this section on the World Ocean Floor map. Note the vertical exaggeration which has the effect of making the slopes seem very much steeper than they actually are.

☐ How are continental mountains distributed about the globe? Look for two main chains of such mountains; is one of these associated with a particular feature in the ocean basins?

☐ How extensive is the distribution of ocean ridges? Do the ridges display any unusual features that make them distinct from continental mountain ranges?

The answers to these questions are contained in the following text.

2.2.3 CONTINENTAL MOUNTAIN BELTS

A **mountain belt** is an elongated mountainous part of the crust, and there are three major belts on the Earth. The first borders the Pacific Ocean: in the east it consists of the Rockies and Andes, and in the west of a more complicated and discontinuous pattern of mountains in Kamchatka, Japan, the Philippines, New Guinea, the Great Dividing Range of Australia and the Southern Alps of New Zealand. This circum-Pacific mountain belt is closely associated with ocean trenches. The second major mountain belt is that of the Alpine–Himalayan chain, which runs approximately west–east from the Mediterranean to south-east Asia and is largely enclosed *within* continental masses. The third major belt is the ocean-ridge system.

2.2.4 OCEAN RIDGES

The ocean ridge shown in Figure 6, which is termed the Mid-Atlantic Ridge (note it is only in the Atlantic that the ridge is situated mid-way between the flanking continental slopes), can be traced northwards through and beyond Iceland, south-eastwards into the Indian Ocean Ridge, and onward into the East Pacific Ridge, which disappears northward under the North American continent. You may be surprised to learn that the *ocean ridge system* is the Earth's largest mountain belt, extending for more than 50 000 km, having an average width of 1 000 km, and rising in places by as much as 5 km (but usually only 2 km) above the flanking abyssal plains. Ocean ridges are formed by processes vastly different from (but not unrelated to, as we shall see) those that have thrown up continental mountains, and these differences are reflected in some of the surface details that are large enough to be depicted on the World Ocean Floor map. Most of the ridges are gashed by numerous fractures that trend perpendicular to their axes, and some of the axes themselves are marked by a central **axial rift**—a steep-sided valley with a flattish floor—as shown in Figure 6. Moreover, the ocean ridges are roughly *symmetrical*, the relief of one flank being the mirror image of the other across the central rift valley. Note, however, that this is not true for small-scale features, but only for the large features depicted on the World Ocean Floor map. The discovery of these characteristics was of immense significance in explaining the origin of nearly all the major features of the Earth's surface, as we shall see once we have examined more data concerning the oceans and continents.

2.3 EARTH PATTERNS

You will probably need to spend about one hour on this Section, and up to 45 minutes listening to the AV sequence 'Crustal patterns' that accompanies it. You should write notes summarizing your answers so that you can refer back to them when using this AV sequence. While studying this Section, you will need the World Ocean Floor map and Figures 7–11 (which fold out from the text at the end of these Units) clearly visible to help you answer the questions. You may need the hand lens from the Experiment Kit to help you read the print on the World Ocean Floor map. Please remember not to mark the map.

CRATON

If you have to divide your study time on this Section into more than one period, we suggest you stop after answering the questions, and spend a later session working through the AV sequence; finally, you should complete the Section by answering SAQs 1–5.

In Section 2.2 some indications of a definite pattern to the distribution of the Earth's surface features began to emerge:

1 The relief of ocean ridges is symmetrical, with one side mirroring the other.

2 In the Atlantic, the ridge is generally equidistant from the flanking continents.

3 The Pacific Ocean is rimmed by a system of continental mountains and ocean trenches.

In Sections 2.3.1–2.3.3, *you* will look for further patterns, involving the age distribution of rocks and the occurrence of active volcanoes and earthquakes, by answering ten questions. You should answer these questions using the information presented in the World Ocean Floor map and in Figures 7–11. The answers to the questions, and further comments, are given in the AV sequence 'Crustal patterns'. Therefore, you should make notes as you answer each of the questions so that you can check your conclusions with those given in this AV sequence.

Note Figures 7–11 are on a fold-out sheet at the end of these Units.

2.3.1 CONTINENTAL PATTERNS

1 The areas of the continents exposing the oldest rocks are known as **cratons**. What kind of relief do they have: are they relatively flat, or relatively rugged? (Look at Figure 7 and the World Ocean Floor map, which also gives an indication of the relief of the continents.)

2 Are these old areas geologically active or inactive (that is, are they characterized by volcanic and seismic activity)? (Look at Figures 9, 10 and 11.)

3 Are mountainous areas (above 3 000 m), such as the Alps, Himalayas and Rockies, composed of relatively young or old rocks (bearing in mind that the Earth is around 4 500 Ma old)? (Look at the World Ocean Floor map and Figure 7.)

4 Do you notice any relationship between those mountain ranges that have volcanism and those that do not, and their proximity to ocean basins? (Look at Figure 9 and the World Ocean Floor map.)

2.3.2 OCEANIC PATTERNS

5 What is the relationship between the relief of the Atlantic Ocean and the ages of the crust that floors it? (Look at the World Ocean Floor map and Figure 8.)

6 Do you notice any relationship between oceanic relief and the distribution of seismic and volcanic activity (for example, are ridges associated with a particular kind of activity, and trenches with another)? (Look at the World Ocean Floor map and Figures 9, 10 and 11.)

7 What are the differences between the Atlantic and Pacific Oceans in terms of:

(a) the symmetry of the relief features they exhibit (is one side roughly the mirror image of the other)? (Look at the World Ocean Floor map.)

(b) the relative rarity of any feature in one ocean compared with the other (for example, are trenches rarer in one ocean than the other)? (Look at the World Ocean Floor map.)

(c) the features exhibited by the margins of the continents that border them? (You should consider continental and oceanic relief, ages of rocks, seismic and volcanic activity. Look at the World Ocean Floor map and Figures 8, 9, 10 and 11.)

2.3.3 CONTRASTS BETWEEN THE FEATURES OF CONTINENTAL AND OCEANIC CRUST

8 What are the differences between the rocks of the continents and those of the oceans in terms of:

(a) the range of ages? Give figures in hundreds of millions of years. (Look at Figure 7.)

(b) the geometric patterns of the distributions (simple versus complex, linear versus concentric, etc.)? (Look at Figures 7 and 8.)

9 What is the difference between the continents and the oceans in terms of the predominant type of volcanic activity? (Look at Figure 9.)

10 What, if any, is the difference between the depth of earthquake foci beneath the continents and the oceans? (Look at Figures 10 and 11.)

2.3.4 CRUSTAL PATTERNS (AV SEQUENCE)

The AV sequence 'Crustal patterns' (Tape 2, Side 1, Band 1) discusses the data presented in Figures 7–11 and the World Ocean Floor map in some detail. Before listening to the tape, you should locate the following features on the map (to help you find them, we have included approximate latitude and longitude positions of the lesser known features; also, there is a key to the World Ocean Floor map in Figure 7):

Feature	Approximate longitude	Approximate latitude
South America		
Africa		
Newfoundland		
Mid-Atlantic Ridge		
Andes		
Alps		
Himalayas		
Rocky Mountains		
Mediterranean Sea		
Black Sea		
Hudson Bay		
Caribbean Sea		
Falkland Islands	60° W	50° S
South Sandwich Trench	25° W	60° S
Alaska		
Anchorage	155° W	65° N
Aleutian Trench (NW Pacific)	160° E	55° N
Kuril-Kamchatka Trench (West Central Pacific)	140–160° E	40–55° N
Japan		
Marianas Trench (West Central Pacific)	145° E	10–20° N
Kermadec-Tonga Trench (West Central Pacific)	170–180° W	10–40° S
New Zealand		
Puerto Rico Trench	60° W	15° N

Now listen to the AV sequence to check your answers to questions 1–10.

2.4 CONCLUSION TO SECTION 2

Perhaps you were surprised to find that all the data on the World Ocean Floor map and in Figures 7–11 fitted into a pattern, with belts of volcanic and seismic activity running around the Pacific, stretching across Eurasia, and running down the centre of the Atlantic. Perhaps you were also surprised to learn that the rocks of the continents are vastly different from those of the oceans, both in age and in the distribution pattern of the ages of rocks forming them. The data concerning the age of the oceans were only accumulated in the late 1960s and early 1970s, but most of the other information you have been studying was known to geologists for most of this

century. So why did it take so long for a theory to emerge that could satisfactorily explain all the features we have discussed? And why did the idea of continental drift (first elaborated with a considerable amount of supporting geological evidence in 1915, as you will see) take so long to become widely accepted by geologists? These questions and the events which led to the revolution of plate tectonics are discussed in Section 3.

SUMMARY OF SECTION 2

1 Deep ocean floor consists of abyssal plains at depths of 4 to 6 km and ocean ridge systems averaging 1 000 km wide, rising generally by 2 km above the abyssal plains. Some of the ridges have axial rifts.

2 Ocean floor is youngest at ocean ridges, and becomes progressively older away from the ridges (up to about 190 Ma).

3 Ocean ridges are sites of shallow seismicity and effusive volcanism. Abyssal plains show little or no seismicity or volcanism.

4 The deepest parts of the oceans are confined to ocean trenches, which are sites of shallow seismicity, and which border volcanic island arcs or volcanic mountain chains.

5 The continental land surface is mostly low lying (within 1 km of sea-level) with little seismic or volcanic activity. These low-lying continental areas are relatively old.

6 Those parts of the continents that are sites of explosive volcanism, or intermediate to deep seismicity, or both, are mountain belts and are over 3 km above sea-level. Areas displaying both volcanism and intermediate to deep seismicity are *almost* all on the margins of the Pacific Ocean. (Exceptions are the Caribbean and Mediterranean areas.)

SAQ 1 Label the section shown in Figure 12 to show the following features:

A continental shelf
B continental slope
C continental rise
D abyssal plain
E ocean ridge
F axial rift valley

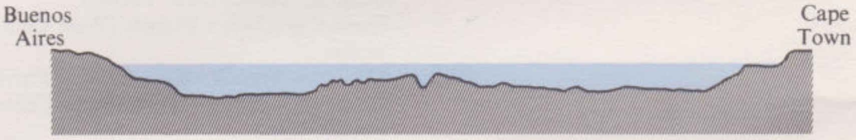


FIGURE 12 For use with SAQ 1.

SAQ 2 Complete Table 2 by describing briefly the principal features of the Earth's crust. We have completed some of the boxes to show the kind of notes intended.

SAQ 3 In two sentences, state why the existence of continents with mountain belts implies a mobile outer part to the Earth.

SAQ 4 How can the frequency distribution curve and the cumulative frequency distribution curve for the elevations of the solid Earth's surface be used to explain the difference between the non-specialist's and the geologist's concept of continents and oceans?

TABLE 2

	Relief[1]	Age of rocks[2]	Seismic activity (including depth of foci)	Volcanic activity (including whether effusive or explosive)
Continental features Cratons	0–3 km, relatively flat			
Young mountain belts not bordering oceans		generally less than 60 Ma, trending E–W from Mediterranean to Tibet and China		rare; except in Mediterranean area, where there is explosive activity
Young mountain belts bordering oceans			very active; shallow on ocean side, becoming deeper inland	
Oceanic features Ocean-basin floors				very little; except for a few volcanic islands with effusive activity
Ocean ridges	2–5 km above ocean basin floors, relatively rugged, traversed by fractures, and some ridges have central rift valley			
Ocean trenches		relatively young and variable (not discussed so far in the text)	[3]	associated island[3] arcs or mountain belts have explosive volcanic activity

Notes

[1] Give approximate elevations relative to sea-level or another datum, such as ocean-basin floor, and state whether relatively rugged or smooth.

[2] Give age ranges, and describe their distribution patterns where appropriate.

[3] Include activity observed on adjacent continental crust.

SAQ 5 Complete Table 3 to describe the major distribution patterns shown by the phenomena discussed in the previous Sections. You should briefly describe their geographical distribution around the globe, and include comments on other patterns such as symmetry, or absence of a feature (in a particular region, or from continental or oceanic crust).

TABLE 3

	Geographical distribution[1]	Patterns/associations[2]	Regions where absent or rare
Rocks older than 1 000 Ma		found in central parts of continents; seismic and volcanic activity largely absent	
Rocks younger than 100 Ma			
Effusive volcanic activity	along central parts of oceanic ridges, on African craton, and scattered within ocean basins away from trenches		on other cratons, and largely absent from young mountain belts
Explosive volcanic activity			central part of ocean basins, most cratons
Zones of shallow-focus earthquakes		associated with effusive volcanism along ocean ridges explosive volcanism along mountain belts and island arcs	
Zones of intermediate- and deep-focus earthquakes			cratons, ocean basins

Notes

[1] Give a simple description, such as 'Circum-Pacific Belt', 'along Mid-Atlantic Ridge', 'landward of ocean trenches'.

[2] In this column you should state whether one feature, such as effusive volcanic activity, is found closely associated with another, such as a certain type of seismic activity. You should also comment on the relationship of age of rocks, and volcanic and seismic activity to the major relief features of the Earth.

CONTINENTAL DRIFT THEORY

3 BEFORE THE REVOLUTION

This Section gives an account of the events that led up to the formulation and acceptance of the plate tectonic theory by the geological community. We have used the names of individual scientists, and quoted from their original publications, to try to give you some impression of science as a human activity, rather than knowledge documented in textbooks. However, you are not expected to remember all these names. A chronological summary of key events in the development of plate tectonics is given at the end of Section 6. Allow about one hour for a first read through this Section.

3.1 INTRODUCTION

Most practising geologists and historians of science agree that the work of a German meteorologist and polar explorer, Alfred Wegener, was 50 years before its time when first published in 1915. In this book, *The Origin of the Continents and Oceans*, Wegener discussed a variety of lines of evidence that he considered favoured the **theory of continental drift**, which encompasses the idea that continents can change their relative positions by drifting apart or converging. In this Section, Wegener's ideas and evidence are summarized, and an account is given of the reactions of contemporary Earth scientists to them in the period leading up to World War II. But we first need to consider the climate of geological opinion in the late 19th century to see why Wegener was 'before his time'.

3.2 BEFORE WEGENER

As early as the 17th century, both Francis Bacon and P. Placet, who was French, were so struck by the similarity of the shapes of the continents on either side of the Atlantic that they speculated on the phenomenon. In 1801 Von Humboldt suggested that the parallelism of shorelines could be accounted for by a vast flood carving a huge valley that is now the Atlantic. In 1858 Antonio Snider postulated that during the cooling period of the Earth the continents formed on one side only, this unstable situation being relieved during Noah's flood by the Old World and the Americas being pulled apart (Figure 13). A similar pulling apart of a continental mass was suggested by the Rev. Ormond Fisher in 1881 to be the result of the birth of the Moon out of the Pacific, which caused the light continental fragments to float towards the newly created depression.

The problem with all these ideas was that they had a *catastrophic* element in them; i.e. they involved unique events of tremendous proportions. Yet in the early part of the 19th century, geology had thrown off its biblical

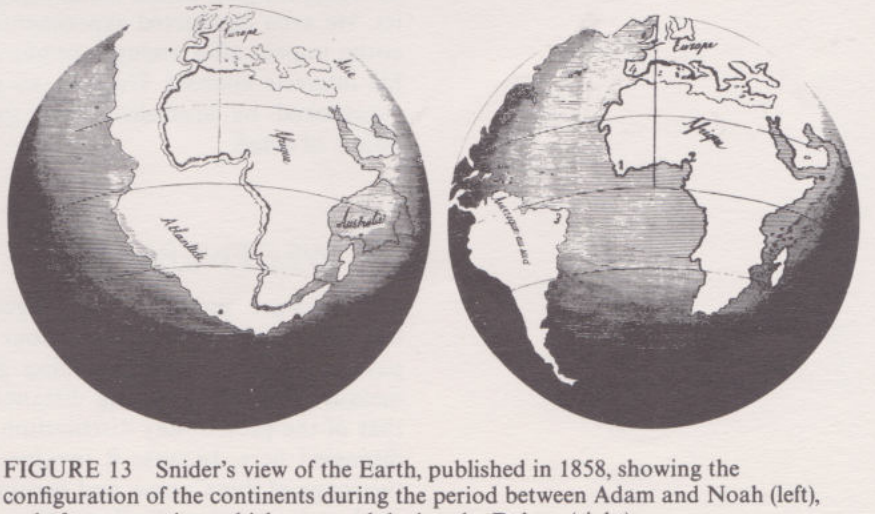


FIGURE 13 Snider's view of the Earth, published in 1858, showing the configuration of the continents during the period between Adam and Noah (left), and after separation, which occurred during the Deluge (right).

ISOSTASY

heritage, which involved floods and 'special creations', and adopted an approach that interpreted past events in terms of processes that can be observed on the Earth as it is today. Thus any hypothesis that smacked of catastrophism—as continental drift did around the turn of this century—was considered to be scientific heresy.

Quite apart from the fact that continental drift implied some kind of catastrophic process, it also contradicted another theory current in the late 19th and early 20th centuries. At this time, the Earth was thought to be cooling down, and many scientists used the rate of cooling to calculate the age of the planet. Their estimates seldom reached 100 million years (compare this with current estimates, which are some 46 times this figure). Cooling implied a shrinking Earth which, it was argued, resulted in the crinkling of the Earth's outer skin to produce mountain belts, much as an apple skin crinkles as the fruit inside dries out and contracts. But continental drift involved at the very least the possibility of crustal blocks moving around independently—an impossible feature to reconcile with a cooling, contracting Earth model in which the continents were pretty well fixed. With the discovery of radioactivity in 1896 and its application to the dating of rocks that rapidly followed (discussed in Units 11–12 and 28–29), estimates of the age of the Earth were considerably lengthened. But it takes time for such new ideas to become accepted by scientists—especially to those in unrelated disciplines. Thus it was many years after Wegener first formulated his ideas on continental drift that geologists in general came to realize the implications of radioactivity as an internal source of the Earth's heat in addition to its usefulness for dating rocks.

3.3 WEGENER AND THE ORIGIN OF THE CONTINENTS: HISTORICAL PERSPECTIVE

In 1910, Wegener first noticed the similarity between the opposing coastlines of the Atlantic when he was examining an atlas map. But it was only in the following year, when he accidentally came across a report summarizing the fossil evidence for a land-bridge uniting Brazil and Africa, that his ideas about continental drift really began to develop. Four months after this accidental discovery, he presented his hypothesis at two scientific meetings, after which he went to Greenland, returning in 1913. At the outbreak of World War I, he joined the German army and served throughout the hostilities, but continued to elaborate his ideas on continental drift. While on sick leave he wrote his book, *Die Entstehung der Kontinente und Ozeane* (*The Origin of the Continents and Oceans*), which was first published in 1915. His work was little known in the English-speaking world until the third edition of the book was reviewed in both the UK and the USA. In 1925 the English translation appeared (and is still in print!). The contents of *The Origin of the Continents and Oceans* are a testament to Wegener's wide interests, ranging across meteorology, palaeontology, geology and geophysics. He even conducted experiments on the origin of lunar craters by meteorite impact after seeing a bright meteor in 1916! Perhaps the breadth of his interests enabled Wegener to see links and patterns which had been overlooked by specialists—but specialists attacked the drift theory on points of detail.

3.4 WEGENER'S CASE

The evidence presented by Wegener in favour of the continental drift hypothesis can be divided into four main groups: continental fit, records of past climatic changes (including glaciation), crustal structure and direct measurement of increasing distances between continents. A fifth category, that of the present-day distribution of land plants and animals, will not be discussed here, because it involves detailed biological knowledge beyond the scope of this Course, and because it is regarded as suspect in the light of modern knowledge. Similarly, Wegener's reports of actual measurements of

the increasing distance between continents over a number of years are now known not to be reliable (indeed, it is only in the last decade or so that reliable methods of measurement have been devised). However, a considerable proportion of Wegener's evidence concerned with continental fit, climatic change and crustal structure has stood the test of time, and is worth considering in more detail.

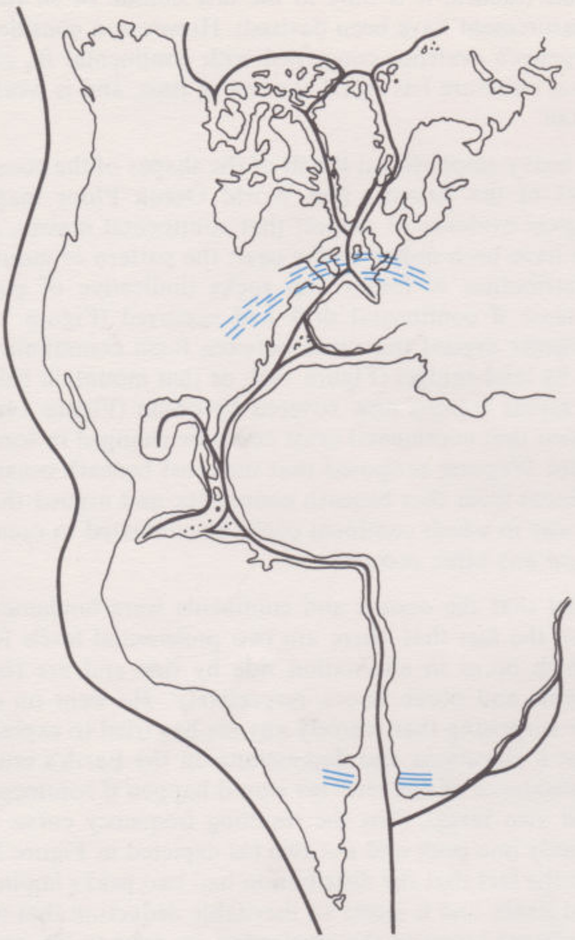
Wegener did not place heavy emphasis on the fit of the shapes of the coastlines on opposing sides of the Atlantic (see World Ocean Floor map). Instead, he cited geological evidence to suggest that continental masses, at present separated, *must* have been united in the past: the pattern of mountain belts, and the distribution of fossils and rocks (indicative of past climates) made more sense if continental drift had occurred (Figure 14, overleaf). Critics of Wegener argued that links between fossil communities could be accounted for by land-bridges (Figure 14b), or that mountain belts were once continuous across regions now covered by ocean (Figure 14a). Such explanations implied that continental crust could be changed in some way to oceanic crust. But Wegener proposed that the crust beneath oceans was fundamentally different from that beneath continents, and argued that there was therefore no way in which continent could be converted to ocean by vertical movements (or any other process).

Wegener based his belief that the oceans and continents were fundamentally different largely on the fact that 'there are two preferential levels for the world's surface, which occur in alternation side by side and are represented by the continents and ocean floors, respectively'. He went on to state that 'it is therefore surprising that scarcely anyone has tried to explain this', and suggested that if elevations and depressions on the Earth's crust were due to uplift or subsidence of one level (as would happen if continents changed to oceans, and vice versa), then the resulting frequency curve of elevations would have only one peak and not two (as depicted in Figure 5). Wegener suggested that the fact that the distribution had two peaks implied 'two undisturbed primal levels, and it seems an inevitable deduction that we are dealing with two different layers in the crust when we refer to the continents and the oceans. To put it in a rather picturesque term, the two layers behave like open water and large ice floes'.

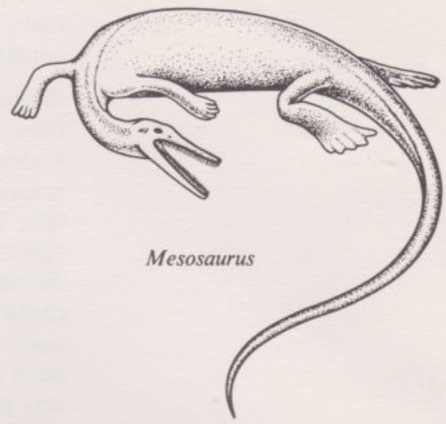
The ice–water model implies that the surface features of the Earth are matched by larger irregularities on the lower surface of the crust, and this state of equilibrium is described by the word **isostasy** (=equal standing). Another simple isostasy model is a piece of wood floating in water. You could easily set up this model at home. If you float a piece of wood in water it will always float with the same volume below the surface. It is in a state of *isostatic equilibrium* or isostatic balance (Figure 15a). If you push the wood down, it will stay down only so long as you keep applying the force—the block is now in a new equilibrium state (Figure 15b). If you stop pushing, it will regain its original position and, in doing so, become isostatically readjusted. Land masses appear to behave just like that piece of wood. If they are displaced from their position of balance by some force they achieve a new state of balance but, once that force ceases to operate, isostatic readjustment takes place until isostatic equilibrium is reached once more. One great difference between the Earth and our wood-in-water

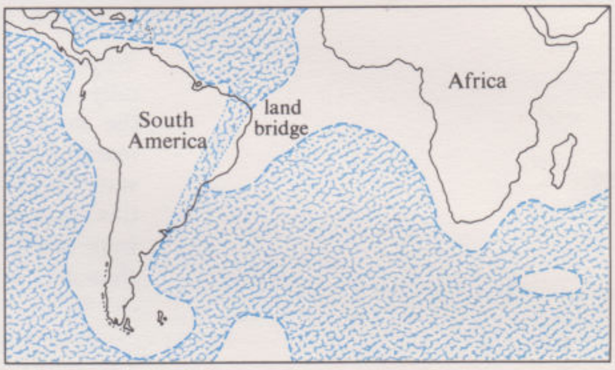
FIGURE 15 Woodblock and water analogy: (a) the block floats freely in water; (b) the block is depressed in water by an external force. See text for further discussion.

FIGURE 14 Some of Wegener's geological evidence for continental drift.

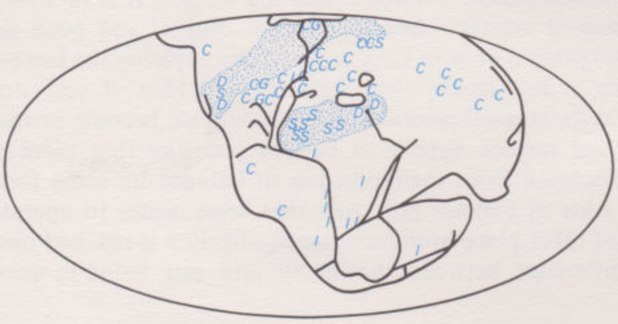


(a) Wegener's Atlantic continent reconstruction, published in 1915. Old mountain ranges (the ages of these were not known accurately in Wegener's time; they are now known to be up to 600 Ma old in North America and Europe, and about 200 Ma in the southern continents) are shown in blue and form continuous belts when the continents are fitted together. Note that Wegener has not fitted coastlines, but the rough positions of continental margins.





(b) Wegener argued that the distribution of fossils of *Mesosaurus*, a small reptile that lived over 200 Ma ago in shallow brackish waters (a mixture of saltwater and freshwater) in South America and Africa, could be best explained by invoking continental drift. The 'conventional' explanation was that a 'land-bridge' connected the two continents and that this later subsided beneath the Atlantic Ocean.



(c) 300 million years ago

(d) 250 million years ago

(c) and (d) Wegener's maps showing climatic belts as they might have existed 300 and 250 Ma ago.

Key for fossil climatic indicators

I Ice

D Desert sandstone

S Salt

G Gypsum

C Coal

Stippled areas indicate arid zones.

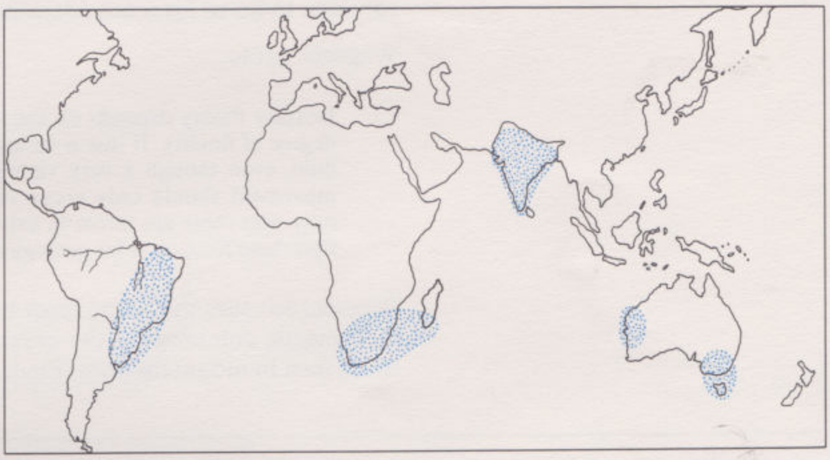
These 'fossil climatic indicators' are discussed in the TV programme 'Drifting continents'. Such interpretations have been refined since Wegener's time, but more modern work has not altered his conclusions.

Desert sandstone, salt and gypsum form in hot, dry regions of the world today. Salt and gypsum are minerals that precipitate from seawater when it is evaporated. Coal is considered to form from the accumulation of plant material that grew in very wet, hot conditions, such as those in present day tropical swamps. On Wegener's reconstructions, the occurrences of coal are on the Equator, and indications of hot,

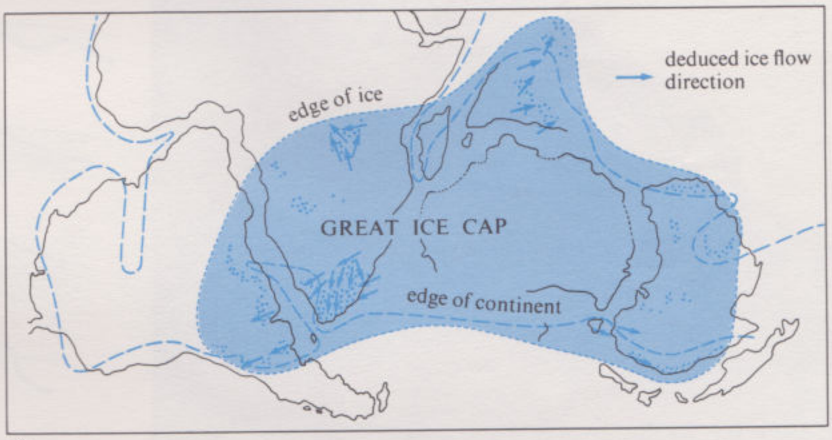
Figure 14 continued

dry conditions flank this area to the north and south—just as African equatorial forests are flanked today by the Sahara and Kalahari Deserts. These maps show that 300 Ma ago, Europe, including Britain, was on the Equator (at which time, the coal in our coalfields was laid down) and 50 Ma later, Europe had moved north to become a desert region (some of the gas fields in the North Sea are found in 'desert sandstones' of this age).

Without invoking continental drift, the south polar ice cap shown in (e) would have covered a huge area of the globe 300 Ma ago, and extended north of the Equator. Note that when the continents are reassembled in their pre-continental drift position (f), deduced ice-flow directions radiate away from a point in central southern Africa, providing yet more evidence in favour of a south polar ice-cap. This ice-cap probably formed in a highland region in the centre of a huge southern continent termed 'Gondwanaland' by geologists. There was probably no thick northern polar ice-cap, as this region was largely ocean 300 Ma ago.



(e)



(f)

analogy is the *rate of adjustment*. The wood takes a fraction of a second to readjust to its equilibrium position, but land masses can be depressed or elevated several kilometres and their rate of readjustment is at the most only a *few centimetres a year*. So a better analogy might be a brick resting on warm tar; the latter is so viscous that it would take days for the brick to sink into it.

A vast quantity of evidence accumulated over the last century shows that isostatic equilibrium is the natural state of the Earth's surface and that isostatic readjustment of any displaced crust takes place continuously (due to the removal of crustal material by weathering and erosion, or the melting of ice caps, to name but two examples). Many Earth scientists consider that the evidence is so strong that the term *law* is applicable to the process—*the law of isostatic readjustment*.

GRAVITY ANOMALY

Can we clarify the picture we have just presented by measuring how much any part of the Earth is out of equilibrium? Yes, we can. It is done by measuring the regional variation of g, the acceleration due to gravity, over the Earth's surface. In many places it is found that g departs from what it should be according to calculation. Such departures are known as **gravity anomalies**, and many of them are caused by the crust being out of isostatic equilibrium. We shall discuss isostasy and gravity anomalies in more detail in Section 4.4.

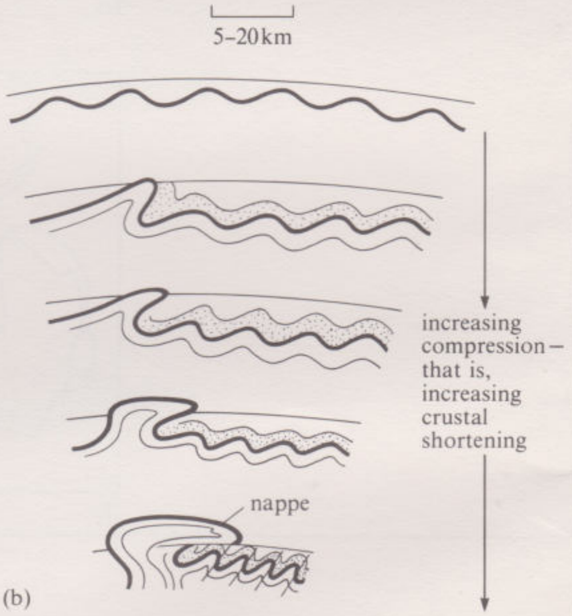
Wegener cited evidence for isostatic readjustment from Scandinavia, where accurate measurements show that the region is rising by as much as $1\,\mathrm{cm\,yr^{-1}}$ (that is, one metre per century). This rise is considered to follow the melting of a thick ice cap that once covered the area, and that caused the crust to sag under the weight. The ice melted away over 10 000 years ago, but the crust is still adjusting to the release of the ice load, and will continue to do so for a considerable time.

Wegener wrote:

> Isostasy theory depends on the idea that the crustal underlayer has a certain degree of fluidity. If this is so and the continental blocks really do float on a fluid, even though a very viscous one, there is clearly no reason why their movement should only occur vertically and not also horizontally, provided only that there are forces in existence which tend to displace continents, and that these forces last for geological epochs.

Wegener felt sure that there must be such forces because the effects of Earth movements, compressing the crust, could be observed from the folding of rocks seen in mountain belts (Figure 16).

(a)



(b)

FIGURE 16(a) Compression of the Earth's crust crumples rocks that were originally horizontally layered to produce these folds, seen in the cliffs of North Devon. These folds were produced during a mountain building period that occurred approximately 250 Ma ago. They provide evidence that the crust in the region was shortened by such movements. Note scale from person in the foreground.

(b) In areas such as the Alps and Scottish Highlands, fold structures termed nappes are found, indicating even greater crustal shortening.

3.5 MECHANISMS FOR CONTINENTAL DRIFT

Wegener called Chapter 9 of his book 'The displacive forces'. He summarized a situation that has applied to the development of many hypotheses and theories in science:

> The determination and proof of relative continental displacements, as shown by the previous chapters, have proceeded purely empirically, that is, by means of the totality of geodetic*, geophysical, geological, biological and palaeoclimatic data, but without making any assumptions about the origin of these processes. This is the inductive method, one which the natural sciences are forced to employ in the vast majority of cases. The formulation of the laws of falling bodies and of the planetary orbits was first determined purely inductively, by observation, only then did Newton appear and show how to derive these laws deductively from the one formula of universal gravitation. This is the normal scientific procedure, repeated time and again.
>
> The Newton of drift theory has not yet appeared. His absence need cause no anxiety; the theory is still young and still often treated with suspicion. In the long run, one cannot blame a theoretician for hesitating to spend time and trouble on explaining a law about whose validity no unanimity prevails. It is probable, at any rate, that the complete solution of the problem of the driving forces will still be a long time coming, for it means the unravelling of a whole tangle of interdependent phenomena, where it is often hard to distinguish what is cause and what is effect.

As we shall see later, although geologists are confident that they have found a source of energy to 'drive' continental drift, the exact nature of the movements within the Earth is still not clear. So it is small wonder that Wegener discussed a variety of possible causes, none of which—unlike the drift theory itself—have stood the test of time. He suggested that drift might be 'powered' by the *Pohlflucht* (flight from the Poles) force, a difference in gravitational force caused by the fact that the Earth is not a perfect sphere, having a polar radius some 21 km smaller than its equatorial radius (see Units 5–6, Figure 2). The value of g is slightly lower at the Equator than at the Poles, because the surface of the Earth is further from the Earth's centre there than at the Poles. This difference might, over long periods of time, be sufficient to cause continental drift. Another force suggested was that of tidal friction: just as the Sun and Moon cause tides in the oceans, so they might in the crust, resulting in a westerly drift. But *Pohlflucht*, though it does exist, is now known to be far too small to cause drift, and if the tidal friction effect *had* worked, then the Earth would have stopped rotating in a matter of days.

3.6 REACTION TO WEGENER: STABILISTS VERSUS MOBILISTS

It is impossible to give an accurate indication of how the scientific community reacts to a new idea even during the time when the debate is actually taking place, let alone some 70 years later. But scientists' habits of organizing and attending conferences to present and discuss new ideas, and then publishing conference proceedings, ensures that the main elements of past controversies, and the postures adopted by individual researchers, are documented for posterity.

In 1922, the British Association for the Advancement of Science held a discussion on the continental drift hypothesis, and in 1926 a similar symposium, at which Wegener was present, was organized by the American Association of Petroleum Geologists. At both these gatherings the reaction to continental drift was overwhelmingly hostile, even sarcastic. One participant went so far as to state that if drift were to be accepted, virtually all the previous results of geological researches would have to be abandoned.

* Geodesy is the science concerned with the measurement of the size and shape of the Earth.

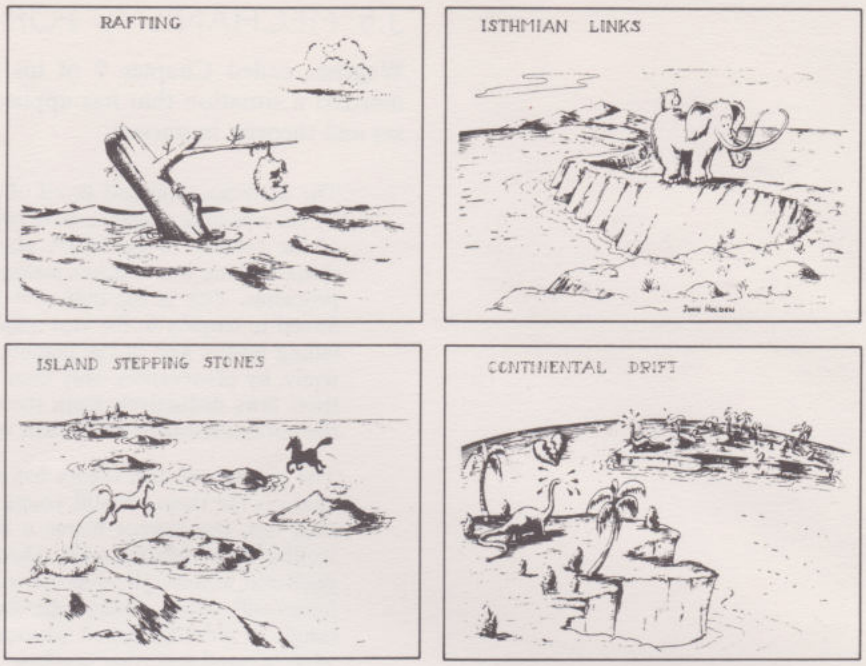


FIGURE 17 An illustration of alternative methods whereby organisms could have migrated between continents. Wegener argued that the distribution of fossil organisms favoured his drift hypothesis, but most palaeontologists at the time favoured a combination of the other processes.

Wegener's continental fits were criticized, largely because he had never discussed them in detail, and apparently had not allowed for the fact that uplift and subsidence at continental margins might have distorted such outlines. His postulation of the existence 300 Ma ago of a single huge south polar ice sheet (see Figures 14e and 14f) was doubted by some on the grounds that it was sited in the interior of a huge continent, and so would not have received heavy snow falls brought in by moist winds blowing over a nearby ocean. These critics thought this huge continent, if it had existed, would have experienced conditions much like those in Siberia today—very cold, but relatively dry. Palaeontologists questioned Wegener's conclusion that similarities between the distribution of fossil plants and animals on now-separated continents *must* imply that drift had occurred between them. They argued that alternative methods of migration, via a few land-bridges, or by island-hopping or even on rafts (see Figure 17 for a more recent view of such ideas) were quite adequate to cause the observed similarities. Wegener's claim that the rate of drift could actually be measured was not accepted, for the simple reason that the majority view was that no means existed whereby such measurements could be made.

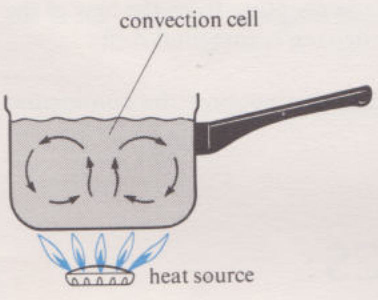
The strongest critics of the continental drift hypothesis were geophysicists, most notable among them Harold Jeffreys of Cambridge University. He and many others believed that the properties of the outer part of the Earth were such that the continents could not plough through the crust, and even if there was a force strong enough to drive them, why was it that only some of their edges were crumpled during drift? Without an acceptable 'driving force', drift theory held little attraction for the majority of geologists, brought up on a diet of vertical crustal movements, which appeared quite adequate to explain the Earth's surface features and its history. So geologists continued their work much as before; despite the discovery that radioactivity provides an internal source of heat, the concept of a cooling and contracting Earth still held sway. The discovery of radioactivity may have lengthened geologists' concept of Earth history, but apparently it had broadened few minds.

But there were geologists who favoured Wegener's ideas, and to an extent this was related to where they worked. Some who had studied the structure of the Alps, or older mountain belts such as that in Scotland, were struck by the fact that major *horizontal* movements had to be inferred from their

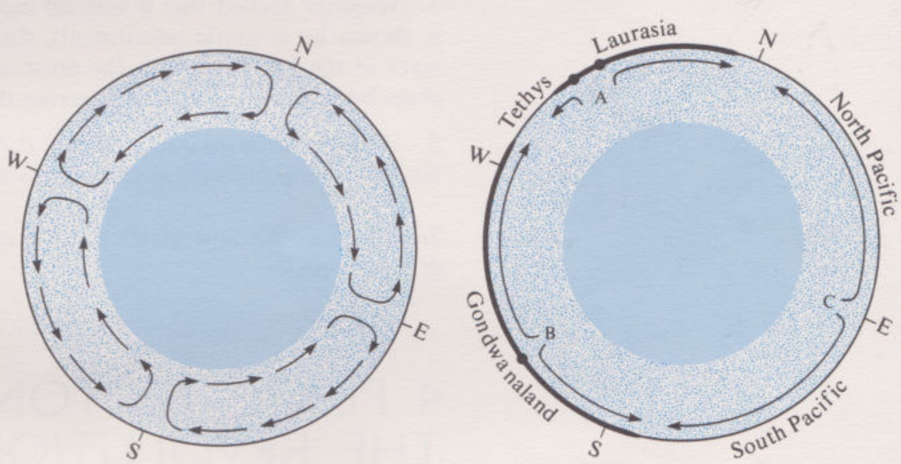
results (Figure 16), and continental drift explained the cause of such movements. Similarly, several Dutch geologists working in the East Indies area of the Pacific, with its frequent earthquakes and volcanic activity, and numerous oceanic trenches, found Wegener's ideas more attractive than the conventional 'stabilist' view. Wegener's most ardent disciple, a South African named Alexander Du Toit, was clearly influenced by his knowledge of the geology of the southern continents, where the evidence for drift is recognized today as being the least equivocal.

Arthur Holmes, working in Britain, and Du Toit suggested that the driving force behind continental drift was produced by systems of convection currents operating within the Earth (Figure 18). Holmes, having pioneered the systematic radioactive dating of rocks, was concerned to find a model that would explain how the Earth lost its internal heat generated as a by-product of radioactive decay. In 1931, he published a paper entitled 'Radioactivity and Earth movements', and later he elaborated his ideas in his classic geology textbook, *Principles of Physical Geology* (1944). In these works, he showed how the Earth's major surface features and continental drift could be related to a system of convection currents 'powered' by heat produced by radioactive decay (radiogenic heat). The upwelling currents, when situated beneath a slab of continental crust, would result in its separation and subsequent migration, much like the behaviour of scum on the top of a pan of boiling jam. Unlike Wegener's model of continents being analogous to floating icefloes on water, Holmes' model moved both the continents and some underlying denser crust, rather than assuming that the continents ploughed through the crust.

FIGURE 18 Convection currents and continental drift.



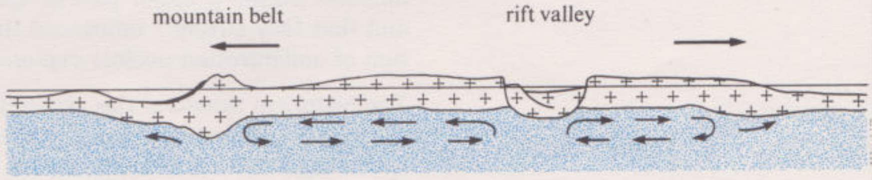
(a)



(b) Holmes 1931

(a) An analogy: in the kitchen, a saucepan of soup or jam simmers, and a system of convection currents is established. Heat from the cooker enters the system at the base of the pan, and is carried upward by the less dense, hotter liquid. Heat is lost at the surface, and so the cooler, denser liquid sinks. In the Earth, the heat source is from radioactive materials in the crust and mantle.

(b) Holmes' hypothesis, published in 1931, shows (left) an idealized convection system within the mantle, and (right) an interpretation of the convection system that might have broken up the southern continent of Gondwanaland (South America, Africa, India, Australia and Antarctica) and the northern continent of Laurasia (North America, Europe, Asia) over 100 Ma ago. The Tethys was a large ocean, the only part of it remaining today being the Mediterranean.



(c) Du Toit 1937

(c) Du Toit's hypothesis, published in 1937, shows a very flat convection system postulated to be rising under rift valleys (See Figure 32a).

Both Holmes' and Wegener's ideas were before their time. It was only after World War II that serious debates began once more, this time stimulated by new results obtained by, of all people, geophysicists. Thus it is ironic that Wegener wrote as follows in the preface to his book:

> I myself in a weak moment once wrote of the drift theory: 'I believe that the final resolution of the problem can only come from *geophysics*, since only that branch of science provides sufficiently precise methods. Were geophysics to come to the conclusion that the drift theory is wrong, the theory would have to be abandoned by the systematic Earth science as well, in spite of all corroboration, and another explanation for the facts would have to be sought'.

You should note, however, that more recent results of geophysical investigations, which we discuss in Section 5.4, suggest that the particular models of convection which Holmes and Du Toit suggested are much too simple.

SUMMARY OF SECTION 3

1 The possibility of continental drift having occurred was first suggested in the 17th century.

2 Wegener reviewed the evidence in favour of the continental drift hypothesis under five main headings:

(a) the fit between continental outlines, especially those bordering the North Atlantic;

(b) geological evidence of past variation in climate;

(c) correspondence of crustal structure in now widely separated continents;

(d) the direct measurement of changing distance between continents;

(e) the present-day distribution of land plants and animals.

3 Wegener argued that if vertical movements of the crust could occur (as is shown by isostatic adjustment), then there must be a plastic (i.e. fluid) layer in the Earth beneath the crust, and that continental drift could take place by horizontal movement across this layer.

5 Holmes proposed convection of the mantle resulting from the loss of the Earth's radiogenic heat as a mechanism for driving continental drift.

SAQ 6 List the four major lines of evidence that support the continental drift hypothesis.

4 PLATE TECTONICS: THE REVOLUTION

Although references to individual scientists, and dates of particular advances, are given in the following Sections, you are not expected to recall these in detail. However, you should recall the general sequence of events: first how palaeomagnetic evidence made geophysicists reconsider their view that continental drift was a physical impossibility, and later how Harry Hess's views on the origin of ocean basins provided a major stimulus to the interpretation of a variety of data. You should also realize that military interests played a major part in sponsoring the exploration of the oceans, and that they strongly influenced the development of seismology for detection of underground nuclear explosions.

The historical thread of this account connects descriptions of a considerable amount of data supporting the theories of continental drift and sea-floor spreading. You should already be able to describe the continental drift hypothesis; after you have finished Section 4 you should also be able to describe the sea-floor spreading hypothesis and, even more important, be able to document the evidence supporting both these hypotheses.

Allow two to three hours for your first reading of this Section.

4.1 NEW EVIDENCE, NEW INSPIRATION

The continental drift debate flared up again in the 1960s, once new evidence from both the continents and oceans had been accumulated. Much of this data was obtained through the use of new technologies, such as palaeomagnetic methods (see Units 5–6), and much more 'routine' and precise methods of dating rocks. For the first time, the ocean floors were systematically surveyed by research vessels, using equipment that owed much of its development to the stimulus of World War II, such as magnetometers and echo-sounders (for mine and submarine detection). This military influence also affected the funding of research. In the USA, a good deal of ocean exploration was paid for by the Office for Naval Research, which had a strong interest in a better knowledge of the oceans because of the developments in submarines that took place in the 1950s and 1960s.

The remainder of Section 4 deals in turn with each category of evidence that led to the formulation of the plate tectonic theory. As far as possible, the evidence is arranged in chronological order. However, bear in mind that developments in one research field were very often taking place at the same time as those in another.

By the end of the 1950s, data were available that stimulated the presentation of a new hypothesis for the origin of the ocean basins. This hypothesis was then tested during the 1960s.

4.2 APPARENT POLAR WANDERING: THE GEOPHYSICISTS RECANT

From the mid 1950s onwards, the results of palaeomagnetic studies conducted at the University of Cambridge and at Imperial College, London, yielded evidence that forced geophysicists to reconsider continental drift as a possibility, despite their reservations that the physical properties of the Earth's outer layers seemed to make it impossible. We discussed this palaeomagnetic evidence in Units 5–6, Section 5, and the discussion may be summarized as follows:

1 Determinations of the positions of the magnetic poles over the last 500 Ma show that the poles *appear* to have wandered during this time.

2 Lines connecting apparent pole positions for a particular continent are called apparent polar wander paths or curves.

3 The fact that apparent polar wander paths from different continents have different shapes for certain intervals of time can only be explained by the movement of the continents relative to each other and to the geomagnetic poles.

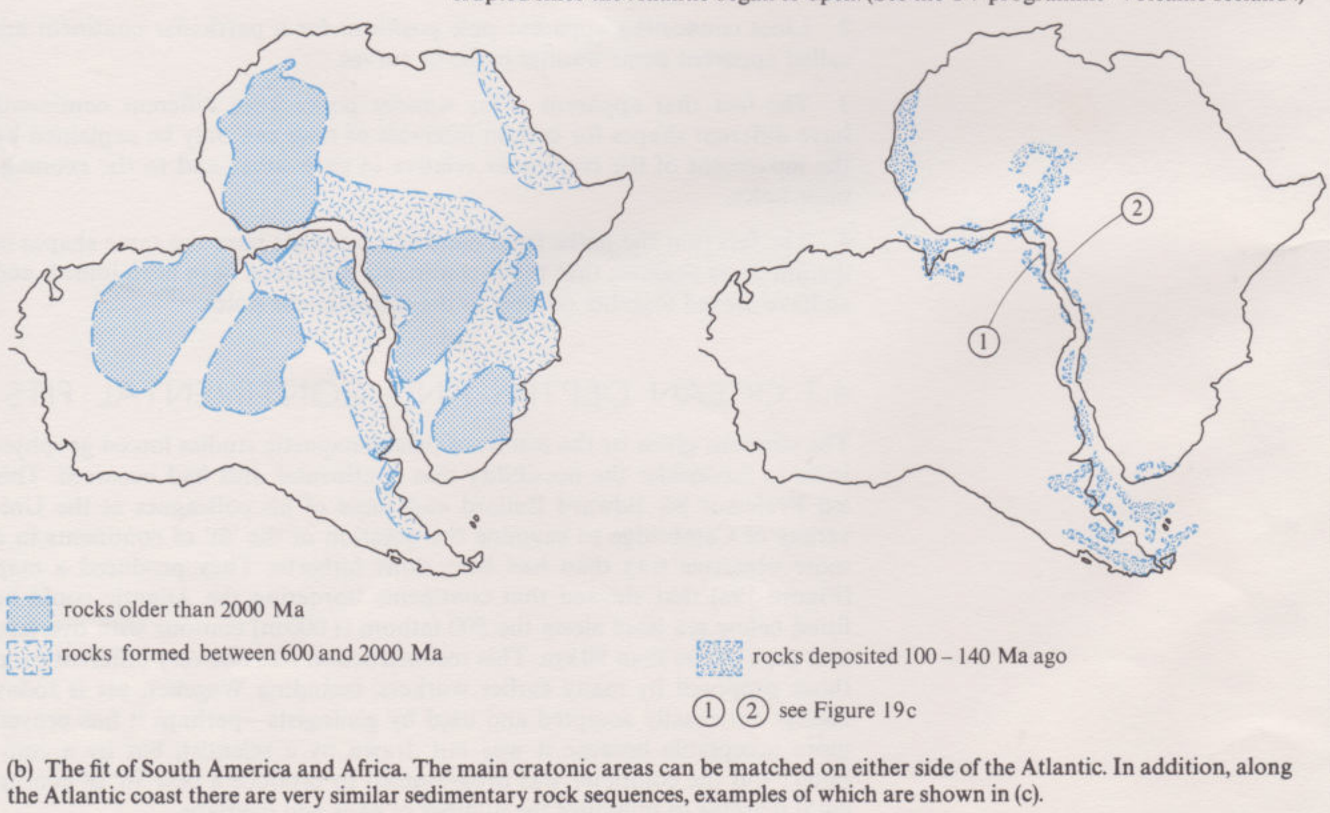
4 The fact that the paths from pairs of continents have the same shapes in certain cases suggests that those continents may once have been joined, and so have moved together relative to the geomagnetic poles.

4.3 OCEAN DEPTHS AND CONTINENTAL FITS

The stimulus given by the results of palaeomagnetic studies forced geophysicists to reconsider the possibility that continental drift had occurred. This led Professor Sir Edward Bullard and some of his colleagues at the University of Cambridge to examine the question of the 'fit' of continents in a more objective way than had been done hitherto. They produced a map (Figure 19a) that showed that continents bordering the Atlantic could be fitted below sea level along the 500 fathom (1 000 m) contour with overlaps and gaps of less than 90 km. This reconstruction was not very different from those proposed by many earlier workers, including Wegener, yet is today almost universally accepted and used by geologists—perhaps it has proved more acceptable because it was not drawn by a scientist, but by a computer! But the computer was programmed to produce a best 'fit' of continental margins to minimize the number of gaps and overlaps.

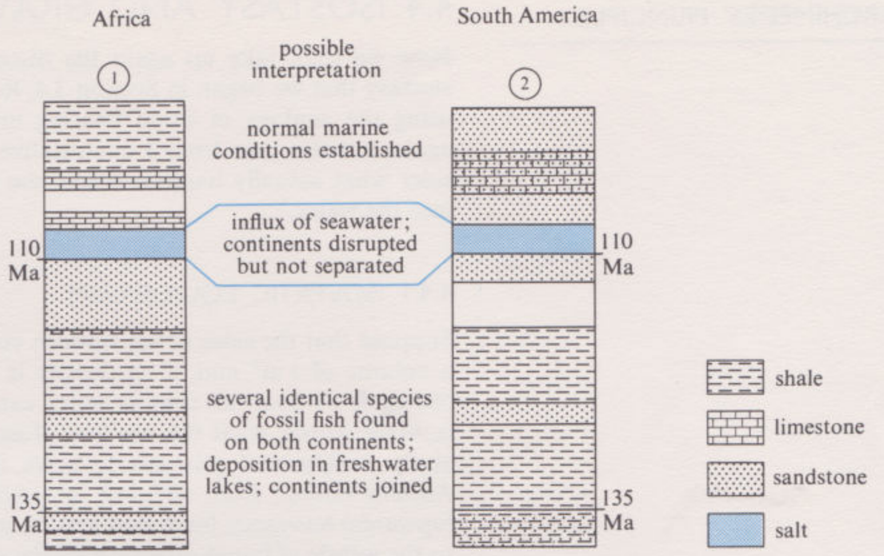
FIGURE 19 Piecing together the continental jigsaw. Evidence that continents now separated by thousands of kilometres of ocean were once joined can be obtained by (a) fitting them together on the basis of their underwater relief; (b) matching the geographic distribution of rocks of various ages; and (c) by comparing sequences of rocks and their contained fossils on either side of oceans.

(a) The fit of the Atlantic continents at the 500 fathom (approximately 1 000 m) contour. Solid colour indicates overlaps; stipple indicates gaps. Some of the overlaps can be accounted for by features that have 'grown' since the Atlantic opened (for example, the Niger Delta and the area off Florida). Note that Iceland is left out of the reconstruction for this reason; it is a pile of volcanic rock that has erupted since the Atlantic began to open. (See the TV programme 'Volcanic Iceland'.)



(b) The fit of South America and Africa. The main cratonic areas can be matched on either side of the Atlantic. In addition, along the Atlantic coast there are very similar sedimentary rock sequences, examples of which are shown in (c).

FIGURE 19 continued



(c) The freshwater sediments on both sides of the Atlantic contain similar fossil fish, and so must have been formed close to one another. The sequence of sediments also contains a record of the first stages of the opening of the Atlantic, with salt deposits being formed by evaporation from a narrow seaway which opened when the two continents were first separated.

Following the publication of the Bullard map, geologists were able to match up the distribution of rock provinces defined on the basis of their ages (determined by radioactive dating methods) on either side of the Atlantic, and they found that the patterns on the 'jigsaw' pieces (that is the ages of rocks on opposing continents) fitted together beautifully (Figure 19b). They also found that younger rocks (less than 140 Ma old) formed at first in freshwater conditions and later in marine conditions were remarkably similar on either side of the Atlantic (see Figure 19c). Such detailed comparisons not only support the hypothesis that Africa and South America were once juxtaposed (because the cratons could be pieced together, and because sediments around 130 Ma old contained the same species of *freshwater* fish), but also give a clue about when drift began (marked by the occurrence of salt from the evaporation of seawater that occupied a narrow gulf between the newly opened continents).

Thus both the depth profile and the geology of continental margins bordering the Atlantic provide strong evidence for the drift theory. But the shape of the ocean floors, which for so long defied explanation in terms of land-based geology, is also significant for the drift theory. The existence of the Mid-Atlantic Ridge was known in the late 19th century, as a result of surveys conducted by cable-laying ships, but Pacific Ocean ridges were only discovered in the 1950s. Similarly, the axial rift zone of some ridges and the incredible symmetry displayed by parts of them (Figure 20) are relatively recent discoveries.

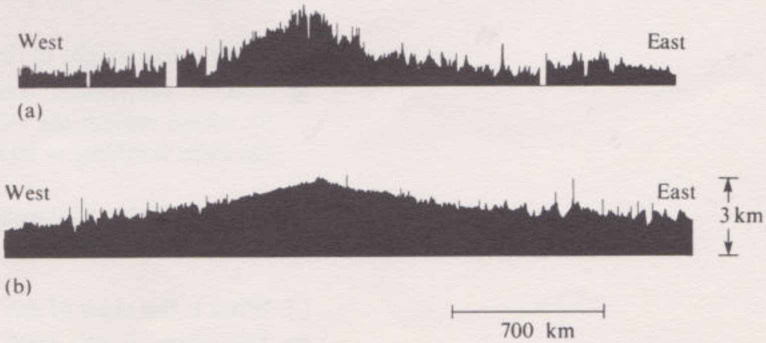


FIGURE 20 Cross-section (a) across the mid-ocean ridge in the North Atlantic and (b) across an ocean ridge in the Pacific. Note the much more 'rugged' relief of the Atlantic ridge and its marked symmetrical (or mirror image across the central rift) appearance. The Pacific example shows a degree of symmetry, but it is much less than that for the Atlantic. The Mid-Atlantic Ridge develops a central rift valley that runs along its length (see the World Ocean Floor map): it is broadly comparable in shape to continental rift valleys, such as the Rhine Rift Valley, and those in East Africa. The pattern of geological faults that produce these rifts is described in Figure 32a. Note that (a) contains three gaps due to the incomplete nature of the survey on which it is based. Note also the extreme vertical exaggeration.

ARCHIMEDES' PRINCIPLE

4.4 ISOSTASY AND GRAVITY ANOMALIES

Now we shall take up again the discussion of gravity anomalies and of isostasy that we began in Section 3.4. Remember that we explained isostasy using the analogy of wood floating on water. Let's look at this analogy again, but this time from a quantitative viewpoint, and then go on to consider what actually happens when you push a wooden cube further down into the water.

4.4.1 ISOSTATIC EQUILIBRIUM

Suppose that the sides of the wooden cube are 1 m long. The cube will have a volume of 1 m^3 and, if its density is 500 kg m^{-3}, it will have a mass of 500 kg. If we float this cube in water, can we tell at what level it will float, or in other words, what the position of isostatic equilibrium will be? We can apply **Archimedes' principle** to solve this problem. (Archimedes lived in Ancient Greece from 287–212 BC.) Archimedes' principle states that the (upwards) buoyancy force that acts on an object floating in a liquid is equal to the *weight* of liquid displaced by the part of the object that is beneath the surface of the liquid. (You may have heard that the realization of this principle apparently came to Archimedes in his bath, whereupon he leapt out and ran down the street shouting 'Eureka', meaning 'I've got it!'.) Now consider the implications of this principle for the wooden cube in Figure 21a. We can find out, using a simple calculation, how far it is submerged in water. For simplicity, we shall take the value for the magnitude of the acceleration due to gravity to be 10 m s^{-2}.

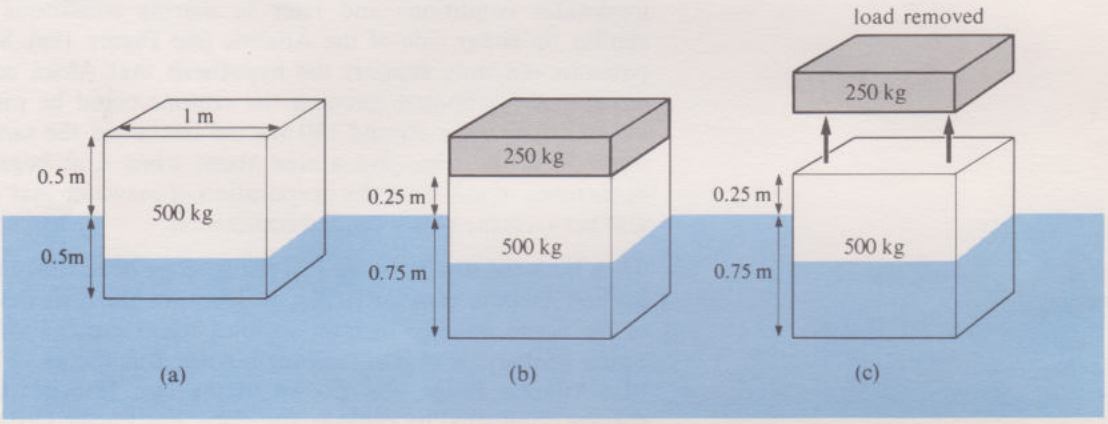


FIGURE 21 A wooden cube with 1 m sides is floating in water (a), and has an extra load of 250 kg placed on it (b). The load is then removed (c).

The cube will be in equilibrium when its weight is equal to the buoyancy force which is, in turn, equal to the weight of the displaced water.

□ What is the weight of the cube?

■ 5 000 N. Remember, weight = mass × acceleration due to gravity (Unit 3), whose magnitude we are taking to be 10 m s^{-2}. Hence the weight of the cube is 500 kg × 10 m s^{-2} = 5 000 N.

The weight of the displaced water, which is equal to the weight of the cube, is therefore 5 000 N.

□ What is the mass of this water?

■ The water *weighs* 5 000 N, so its mass is 5 000 N/10 m s^{-2} = 500 kg (i.e. the same as the mass of the cube).

□ What is the volume of the displaced water?

■ 0.5 m^3. Because density = mass/volume, it follows that volume = mass/density. The density of water is 1 000 kg m^{-3}, so the volume of displaced water is 500 kg divided by 1 000 kg m^{-3}, which is 0.5 m^3.

□ How far will the cube be submerged in the water?

■ 0.5 m. The cube will be exactly half-submerged because the volume of water displaced is $0.5\,m^3$ while the total volume of the block is $1\,m^3$.

Now consider what will happen if we place a mass of 250 kg on top of the wooden cube, and allow the cube to adjust to a new level of isostatic equilibrium (Figure 21b). According to Archimedes' principle, an extra amount of water weighing 2 500 N will be displaced to obtain equilibrium. Since, $0.25\,m^3$ of water weighs 2 500 N, the cube will now float with three-quarters of its volume submerged, i.e. $(0.25 + 0.5)\,m^3$.

If the mass of 250 kg is removed, the cube will bob up to its half-submerged position again. However, if we do the experiment in a very viscous liquid, such as treacle, then the restoration of equilibrium will take a lot longer. So at the moment the mass is removed (Figure 21c), the cube is not in isostatic equilibrium; there is a mass of fluid 'missing' beneath the block. This missing mass will be restored as the treacle flows in beneath the cube, which will therefore rise. Conversely, if we think of the situation at the moment that an *extra* mass is placed on the cube, there will be some 'excess' mass beneath the cube, which will flow out as the cube sinks back to equilibrium.

The detection of either excess or missing mass below a floating object can therefore tell us whether or not the object is in isostatic equilibrium. All this has geological relevance because it turns out that significant parts of the Earth's crust are *not* in isostatic equilibrium.

□ Can you suggest how we might detect excesses or deficiencies of mass, in order to discover whether or not particular parts of the Earth's crust are in isostatic equilibrium?

■ We could measure the magnitude of the acceleration due to gravity, since the value of g depends on, among other things, the mass of the material underneath the particular part.

4.4.2 VARIATIONS IN g: GRAVITY ANOMALIES

Let's consider in more detail how measuring g would help us detect excesses or deficiencies. You will recall from our discussion of gravitational attraction in Unit 3 that the gravitational force between two objects depends upon both their mass and their distance apart. On the Earth, the only variation of which we are normally aware is in the mass of the *objects*—the mass of the Earth is essentially fixed for everyday purposes—and most of us spend most of our time at a more or less constant distance from the centre of the Earth. So g appears constant to the casual observer.

We also said in Unit 3 (Section 6.1) that in working out the gravitational force on an object on the Earth's surface we could assume that all the Earth's mass is concentrated at its centre. However, this assumption is only true if the Earth's mass is arranged with perfect radial symmetry, or in other words if the density of any bit of the Earth depends only upon its distance from the centre. In practice, this assumption of symmetry is not true of many parts of the Earth's crust (or indeed, of the upper mantle, as you will see in Section 5.4). The net effect of these density variations is that the acceleration due to gravity varies over the Earth's surface. The variations (gravity anomalies) are very small, ranging up to about 1/10 000 of the average value of g, but with sensitive gravity meters these variations can be readily detected.

A gravity anomaly at a point on the Earth's surface is defined as the amount by which the *observed* value of g differs from the theoretical, calculated value. This calculated value is obtained by (a) assuming that the Earth's density is radially symmetrical, and (b) allowing for the fact that the Earth is slightly flattened at the poles as a consequence of its rotation (Units 5–6).

An absence of isostatic equilibrium produced by an excess of mass corresponds to a higher value of g than would be expected for a radially

MILLIGAL

ASTHENOSPHERE

LITHOSPHERE

symmetrical Earth, and this is termed a positive gravity anomaly. A deficiency of mass produces a lower than expected value of g, or a negative gravity anomaly.

The unit traditionally used in gravity anomaly work is the **milligal** (abbreviated to mgal), which is defined as an acceleration of $10^{-5}\,\mathrm{m\,s^{-2}}$. A milligal is a thousandth of a gal, which was named after Galileo. Note that these are not SI units—they were defined in this way before SI units were internationally accepted for scientific use. Remember that the magnitude of the acceleration due to gravity at the Earth's surface is about $10\,\mathrm{m\,s^{-2}}$, so a milligal is about a millionth of the value of g. A positive gravity anomaly (excess of mass) is given a plus sign (e.g. $+10$ mgal) because the actual gravitational acceleration is locally greater than the theoretical value, due to the extra mass *below* the surface. A negative anomaly (deficiency of mass) is given a negative sign (e.g. -15 mgal).

An interesting example of isostatic adjustment is found in Scandinavia. During the last Ice Age, a thick ice-sheet developed over this area and, as a result of this extra load, the crust was depressed. When the ice-sheet melted about 10 000 years ago, the crust began to rise again to reach a new isostatic equilibrium (Figure 22). This uplift is still going on, so you can see that the time-scale for isostatic adjustment is of the order of at least 10^4 years.

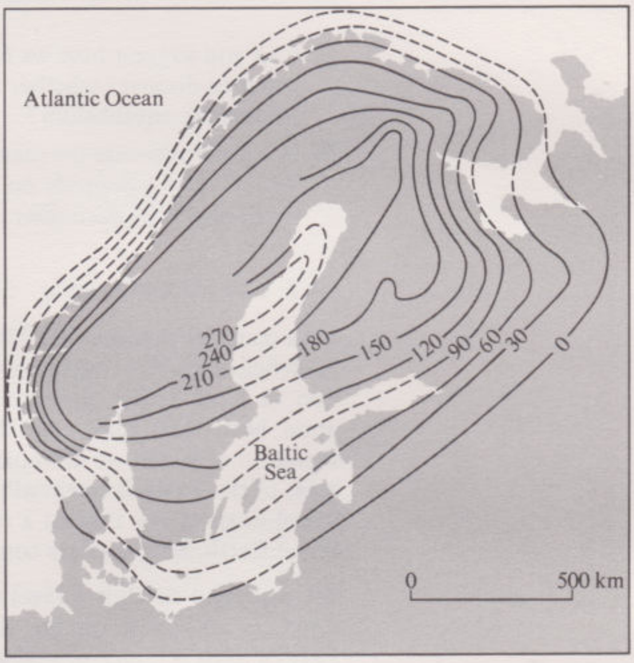


FIGURE 22 Map showing the amount of uplift of Scandinavia since the melting, about 10 000 years ago, of the ice-cap that covered the region. The area is still being uplifted today. Contours are in metres of uplift.

ITQ 1 Will the Scandinavian region shown in Figure 22 be characterized today by a positive gravity anomaly or by a negative one?

4.4.3 HOW DOES ISOSTASY OPERATE IN THE EARTH?

One of the important implications of isostasy is that some part of the mantle beneath the crust can move to accommodate the vertical movement resulting from addition or loss of mass within the crust. However, we have not addressed the question of how the mantle can behave in this way. In Units 5–6, we established quite clearly, from the behaviour of seismic waves, that the materials of the mantle are elastic. In order for isostasy to operate, however, there must be material that can flow (in other words, exhibit ductile behaviour). The seismic evidence shows that the material is not liquid, so it must be a ductile solid. But how can evidence for the presence of a ductile material be reconciled with the seismic evidence for the presence of an elastic material?

The answer lies in the properties of solids. The elasticity or otherwise of a solid depends not just on its intrinsic properties, but also on both the amount of force applied to it and the *length of time* for which the force is applied. The effect of a large force applied for a very long time to a lump of rock is that the rock will flow, albeit very slowly. However, if the same rock is suddenly hit with a hammer it will behave elastically, and the hammer blow will be transmitted elastically as a P-wave through the rock. Toffee also behaves in this way. If you try bending a piece of toffee gently in your fingers, it just gives, and the piece becomes curved. It doesn't spring back to its original shape, so it is showing ductile behaviour. On the other hand, if you mould the toffee into a ball and drop it onto a hard surface, it will bounce a little. As it bounces, the toffee distorts slightly and then immediately returns to its original shape; in other words, it shows elastic behaviour when distorted quickly.

Many solids show this dual behaviour: elastic when deformed quickly, but ductile when deformed very slowly. This explains why the sudden shock waves from earthquakes or explosions are transmitted through the mantle elastically, while gradual loading or unloading of the crust can be accommodated, and isostatic equilibrium restored, by very gradual flow of the ductile mantle material beneath the crust. As you will realize, the timescale of geological processes, being so much longer than that of everyday experience, is hard to comprehend.

Ductile behaviour of the mantle also depends on the temperature of the material. Where the temperature is higher, the material will more readily show ductile properties. We saw in Units 5–6, Section 1.3.1 that the temperature in the Earth's mantle increases with depth quite rapidly.

4.4.4 THE ASTHENOSPHERE AND THE LITHOSPHERE

The part of the mantle that flows to accommodate isostatic adjustments is referred to as the **asthenosphere** ('astheno' coming from the Greek word for weak). As the uplift of Scandinavia demonstrates (Figure 22), the timescale of isostatic adjustment appears to be at least 10^4 years. The part of the Earth above the asthenosphere is essentially rigid on the timescale of isostatic adjustment, i.e. it does not flow. This layer includes the crust and the uppermost parts of the mantle, and is called the **lithosphere** ('lithos' meaning rock). The thickness of the lithosphere varies around the Earth (Figure 23). Beneath ocean ridges, the lithosphere is much thinner than average. The temperature at any given depth is higher than elsewhere, as you will learn in the next Section; consequently, the mantle becomes ductile at much shallower depths than elsewhere, and so the base of the lithosphere is shallower. The lithosphere thickens away from the ocean ridge as the material becomes cooler. As a rough guide, the oceanic lithosphere reaches its maximum thickness of about 100 km in, for example, those parts of the North Atlantic where it is over 100 Ma old (Figure 8).

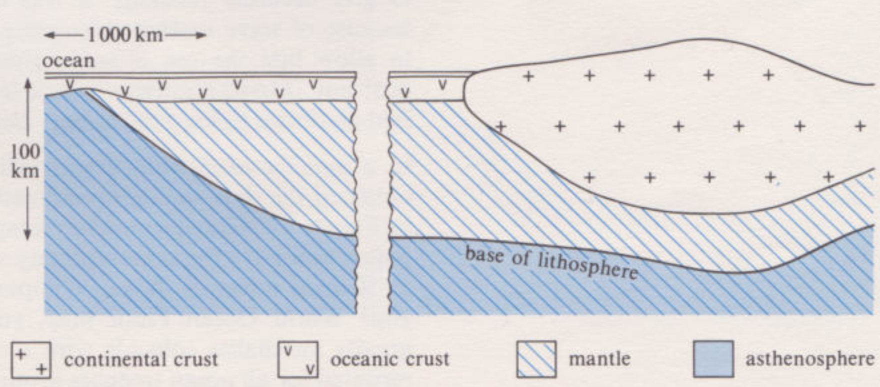


FIGURE 23 Diagram showing the proportions of mantle and crust making up the lithosphere, and how the proportions vary from place to place.

WADATI–BENIOFF ZONE

The thickness of the lithosphere beneath the continents is rather less certain. The crust varies in thickness from 90 km (beneath the Himalayas) to 20 km, with an average of around 33 km. In areas underlying old continental crust (the cratons referred to in the AV sequence 'Crustal patterns'), where there is low heat-flow, the upper mantle has distinctive properties down to about 200 km depth. This suggests that the lithosphere may be up to 200 km thick in places. According to some seismologists, the distinctive properties of the upper mantle go even deeper. Indeed, the seismic line surveyed by the USSR scientists using nuclear explosions (referred to in the TV programme 'Earthquakes: Seismology at work' which is part of Units 5–6) gave results which suggested that these seismic differences are present at depths as great as 400 km beneath central USSR. However, the asthenosphere is not defined on seismic criteria, so that the significance of seismic data has to be carefully evaluated before it can be used in a discussion of lithospheric thickness.

You should note that the asthenosphere, as we have defined it here, is not the same thing as the seismic low-speed layer that we discussed in Section 4.4 of Units 5–6. The low-speed layer is a zone in which seismic wave speeds are reduced, and so the layer is defined only on seismic criteria. The definition of the asthenosphere on the other hand has nothing to do with seismic considerations. It is simply the part of the mantle that shows ductile behaviour and can accommodate isostatic adjustments.

Studies of the ductile behaviour of rock at high temperatures and pressures, and of heat-flow, suggest that the top of the asthenosphere has a temperature of around 1 000 °C. In contrast, the peridotite of the upper mantle only becomes partially melted at a greater depth, where the temperature is above 1 200 °C. So, in general, the top of the low-speed layer is below the lithosphere–asthenosphere boundary. In fact, the low-speed layer lies within the asthenosphere, and varies in depth from around 50 km to as much as 200 km beneath the deeper parts of the continental crust. However, the seismic evidence shows clearly that, unlike the asthenosphere, the low-speed layer is not present everywhere around the Earth. Where the layer is absent, the crust is old, relatively cool, cratonic continental crust. This implies that there are some parts of the asthenosphere in which the conditions are such that the partial melting that gives rise elsewhere to the seismic low-speed layer does *not* take place.

4.4.5 OCEAN TRENCHES: GRAVITY ANOMALIES AND EARTHQUAKES

Now we turn to the pattern of gravity anomalies associated with ocean trenches. These were first mapped out in the East Indies by the Dutchman, Vening Meinesz, in the period 1923–30. At that time, gravity meters were much less sensitive than they are today, and they needed a stable platform to give accurate readings. It was impossible to use the meters on ships because of wave motion. Meinesz persuaded the Royal Netherlands Navy to allow him the use of submarines for his work, to avoid this stability problem. (Modern gravity meters for ocean work have dynamically stabilized platforms to keep the gravity meter horizontal.)

In a number of strenuous and tedious expeditions over several years, he obtained the data that are presented in the form of a gravity anomaly map in Figure 24. Gravity anomaly maps are made by drawing lines through points that have the same anomaly values. In Figure 24, the lines are drawn at 50 mgal intervals. If you compare Figure 24 with the same region on your World Ocean Floor map, you will realize that the large negative gravity anomalies coincide with a deep ocean trench. This relationship is repeated for all ocean trenches around the world.

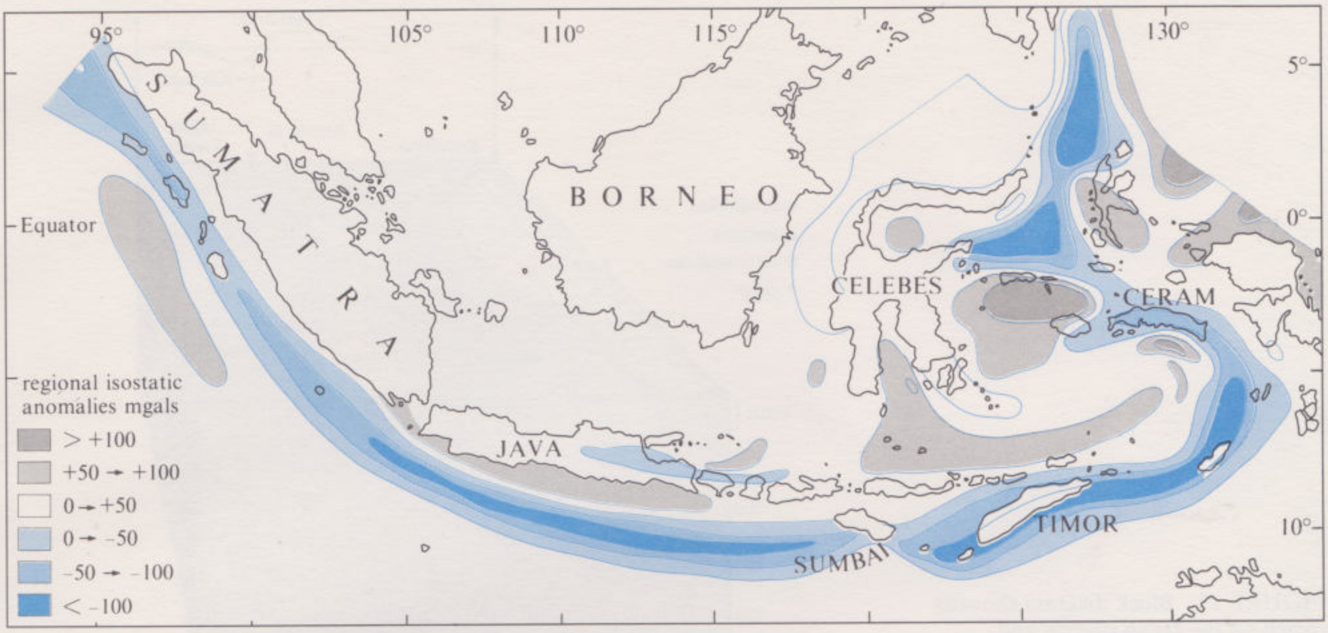


FIGURE 24 Simplified gravity anomaly map of the East Indies. The blue areas exhibit negative gravity anomalies.

☐ What do these large negative gravity anomalies indicate about ocean trenches?

■ Clearly the trenches are not in isostatic equilibrium, and there must be a deficiency of mass to produce the negative anomalies. You saw the same pattern for Scandinavia in ITQ 1.

However, in the East Indies, unlike the Scandinavian region, there is no evidence that the ocean floor is rising to restore isostatic equilibrium. The area is being kept in a state of *disequilibrium* by some means.

☐ Can you suggest a mechanism that could maintain disequilibrium?

■ It must be a dynamic mechanism. Once-and-for-all removal of mass would be compensated for by movement of material in the asthenosphere. But a process of continuous movement of material away from the region could exert a frictional drag on the oceanic lithosphere that keeps it permanently pulled down, as if it were on a downgoing conveyor belt.

This was the suggestion made by Meinesz; he thought that the downwards pull might be associated with the descending parts of what we now know to be the lithosphere. He thought of the process in terms of convection currents like those suggested by Holmes and Du Toit (Figure 18). We shall discuss these ideas further in Section 5.4.

Such a mechanism accounts for the negative gravity anomalies, as well as for the existence of the deep trenches. It also explains the distribution of earthquakes, as you will see next.

In the 1950s, Hugo Benioff of the California Institute of Technology used improved seismic techniques to plot with considerable accuracy the location and depth of earthquake foci associated with ocean trenches. It was the Japanese seismologist, Wadati, who in 1934 found that there are sloping zones of earthquake activity associated with trenches that are inclined towards the continents. These inclined earthquake zones are now known as **Wadati–Benioff zones**. If you refer back to Figures 10 and 11, you can see the location of some of the larger Wadati–Benioff zones around the Pacific since they are the only regions where deep-focus earthquakes occur. Note that the term Wadati–Benioff zone is relatively new; in older texts these zones are referred to as Benioff zones.

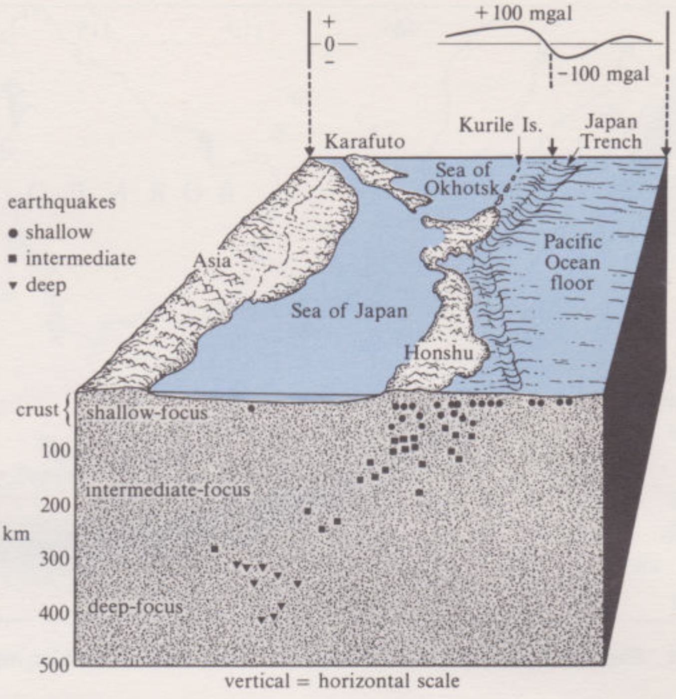


FIGURE 25 Block diagram showing trench off the Japan islands, and associated gravity anomalies and earthquake activity.

Figure 25 is a block diagram showing the relief and earthquake distribution at depth in the region of the Japan islands. The negative gravity anomaly over the trench is also shown, together with an associated positive anomaly over the islands themselves.

ITQ 2 What other kind of geological activity is associated with Wadati–Benioff zones?

□ What measurements might provide evidence for the idea that trenches are over the sites of descending, relatively cool oceanic lithosphere?

■ Measurements of heat flow. The amount of *heat* flowing from the crust in trenches would—if the convection hypothesis were correct—be lower than average. Such measurements are the topic of Section 4.5.

SAQ 7 Examine Figure 26. Given that block (b) is in isostatic equilibrium and all blocks have the same density, indicate which models will give negative gravity anomalies and which will give positive ones. Which model will give the largest positive anomaly and which will give the largest negative anomaly?

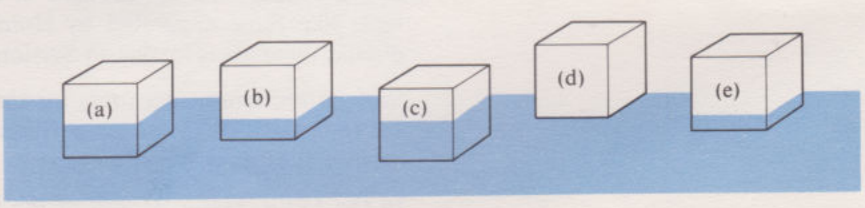


FIGURE 26 Woodblocks in water. Block (b) is floating freely, and so is in isostatic equilibrium. For use with SAQ 7.

4.5 MEASURING OCEANIC HEAT FLOW

Instruments capable of measuring heat flow in oceanic crust were developed only after World War II, although such measurements had been made on land since the end of the 19th century. Basically, the technique of heat-flow measurement in the Earth's crust is quite simple: temperature measurements at two depths beneath a particular point are needed, plus a measure of the 'thermal conductivity' of the material in between.

We do not need to discuss a precise, quantitative definition of thermal conductivity here; at a qualitative level the concept is familiar from everyday

experience. Fill a metal container with boiling water, and almost immediately its outer surface is too hot to touch. But in a polystyrene container the outflow of heat from the hot inner surface is much slower, so you can pick the container up. The difference between the speed at which the outer surface of the two containers heats up is largely a reflection of their different thermal conductivities, metal having a higher thermal conductivity than polystyrene or china.

To make a heat-flow measurement, we need to know the temperature difference between two points. The larger the space between the points, the more accurate the heat-flow measurement. On land, heat-flow measurements can be made in mineshafts or boreholes, so that it is quite easy to get a large spacing between the points, but seasonal changes in temperature can complicate the measurements. Fortunately, measurements beneath the deep-ocean floor are not complicated by seasonal changes in temperature (deep-ocean water generally stays at the same temperature throughout the year so that crustal temperatures, unlike those beneath land surfaces, are not subject to seasonal variation), so it is not as important to have a large space between the measurement points.

Before oceanic heat-flow measurements were made, it was confidently expected that such values would be *lower* than those obtained on land. The reason behind this expectation was that there was likely to be a higher concentration of radioactive heat production in the continental crust than in the oceanic crust that was assumed to underlie the oceans. To the surprise of all concerned, the oceanic heat-flow values turned out to be much the same as those for the continents. Later observations of oceanic heat flow showed that whereas ocean basin floors show 'average' heat-flow values, ocean ridges are 'hotter', and trenches 'cooler' (Figure 27). Bullard, who had contributed to early designs of the apparatus used to obtain the first unexpected results, suggested that convection currents in the mantle, rising under ocean ridges and plunging beneath the continents at the sites of ocean trenches, would account for the new data. Thus, oceanic heat flow is due to heat escaping from the mantle at ocean ridges, whereas continental heat flow is largely due to the heat released over a long period of time by radioactive material present in continental crustal material.

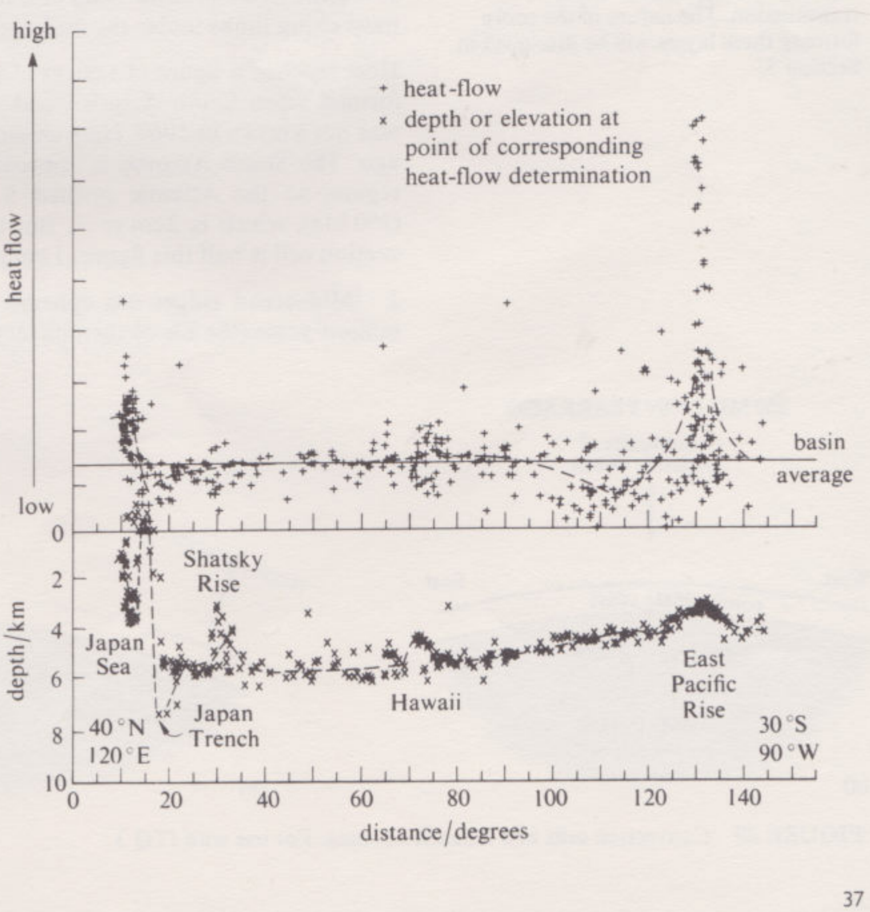


FIGURE 27 Profiles of heat flow and relief across the Pacific. Heat-flow units are not defined in this Course; the main point to note is that heat-flow values are well above average over the East Pacific Rise, and below average in the Japan trench.

SEA-FLOOR SPREADING

4.6 AN ESSAY IN GEOPOETRY

In 1960, Professor Harry Hess of Princeton University circulated a draft of a paper that was not formally published until 1962, but even in its 'pre-print' form (the term used by scientists when circulating drafts of papers to colleagues) it had a profound influence on other workers. Hess called his paper 'an essay in geopoetry', and introduced it by concisely summarizing the contemporary state of knowledge of the oceans by stating 'The birth of the oceans is a matter of conjecture, the subsequent history is obscure, and the present structure is just beginning to be understood'. The paper contained no new data: it was speculation based on a synthesis of existing knowledge.

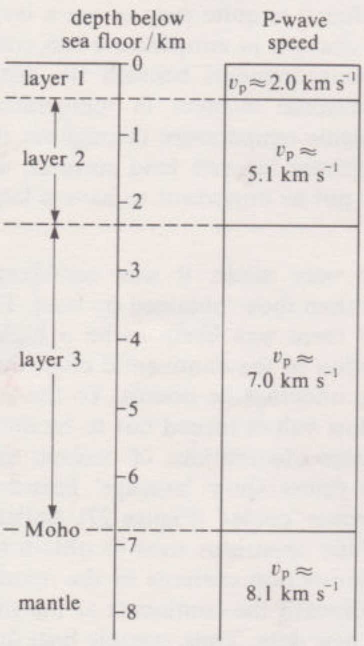


FIGURE 28 Seismic layers of oceanic crust; the thickness of the layers is remarkably uniform over all the oceans. The column shows the thickness of each layer, and its speed of P-wave transmission. The nature of the rocks forming these layers will be discussed in Section 5.

Hess was struck by the uniformity of the thickness of the layers within oceanic crust as deduced from seismic studies (Figure 28) and wondered what kind of process was responsible. He was sure that outpourings of basaltic lava (which were known to floor the oceans beneath a thin layer (layer 1) of sediments) would not produce uniform layering, as they would thicken towards the vent, or fissure, from which the lava came. The details of the process suggested by Hess to account for the uniform layering need not concern us here, but the conclusions that followed from it are extremely important, and had a profound effect on the interpretations made by other researchers in the 1960s.

The most important speculations made by Hess are outlined below, and following them are ITQs which will require you to consider both how they were arrived at, and their significance in interpreting the origin of some of the features you have already studied. *It is important to note that when Hess made these speculations, knowledge of the age distribution of rocks flooring the ocean was extremely scanty. The information given in Figure 8 did not exist at that time, therefore you should not use it when answering these questions.*

Hess's speculations

1 'The mantle is convecting at a rate of 1 cm yr^{-1} and the convecting cells have rising limbs under the mid-ocean ridges'.

Hess reached a figure of 1 cm yr^{-1} by assuming that the South Atlantic had formed when South America and Africa broke apart, the timing of which was not known in 1960. Hess assumed that break-up began roughly 250 Ma ago. The South Atlantic is approximately 5 000 km wide in the equatorial region, so the Atlantic opened 5×10^8 cm (5 000 km) in 25×10^7 years (250 Ma), which is 2 cm yr^{-1}. But the movement on each limb of the convection cell is half this figure: 1 cm yr^{-1} (Figure 29).

2 'Mid-ocean ridges are ephemeral features having a life of 200 to 300 million years (the life of the convecting cell) ... The whole ocean is virtually

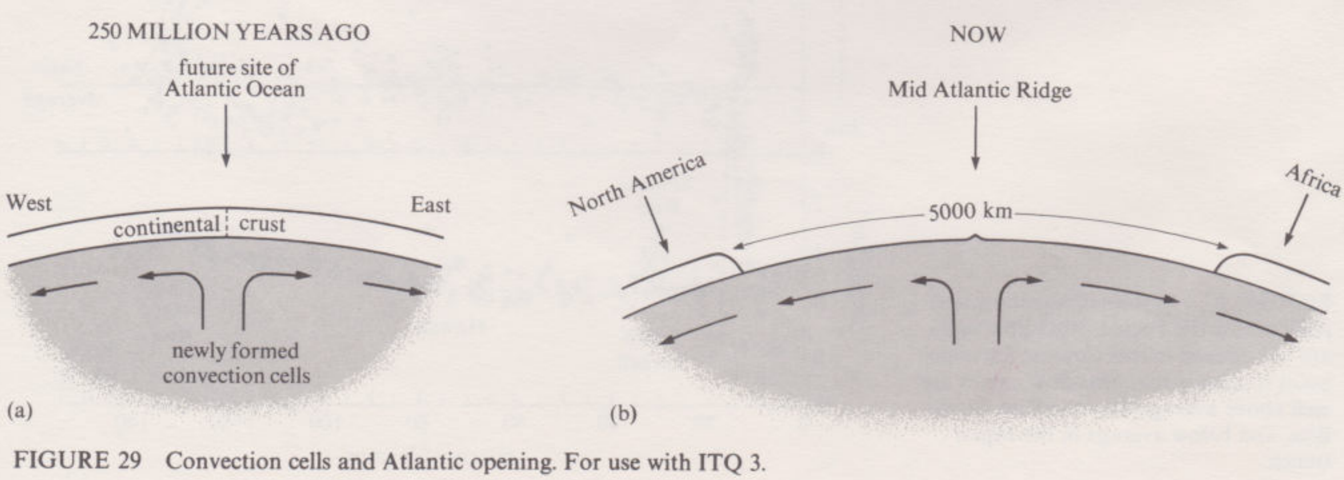


FIGURE 29 Convection cells and Atlantic opening. For use with ITQ 3.

swept clean (replaced by new mantle material) every 300 to 400 million years'.

3 'Rising limbs coming up under continental areas move the fragmented parts (of continents) away from one another at a uniform rate so a truly median ridge forms as in the Atlantic Ocean.'

4 'The continents are carried passively on the mantle with convection and do not plough through the oceanic crust.'

5 The leading edges of continents 'are strongly deformed when they impinge upon the downward moving limbs of convecting mantle. The oceanic crust, buckling down into the descending limb, is heated... The cover of oceanic sediments and the volcanic seamounts also ride down into the jaw crusher of the descending limb, are metamorphosed* and eventually are probably welded onto continents.'

ITQ 3 (Speculation 1) Figure 19c provides a more precise date for the time the South Atlantic began to open, for it is probable that the occurrence of salt marks the influx of seawater into a narrow gulf between the two continents. What rate of movement on *one* limb of the postulated convection cell does this revised date of opening give?

ITQ 4 (Speculation 1) Hess cited evidence that supported the idea that ocean ridges are underlain by upwelling convection currents. You have already met *three* lines of evidence: what are they?

ITQ 5 (Speculations 2 and 3) What observation would most aid the verification of these speculations? (This is not a catch question—the answer is quite simple!)

ITQ 6 (Speculation 4) How does this description differ from Wegener's concept of drifting continents?

ITQ 7 (Speculation 5) You have already met evidence that supports these ideas of the leading edges of continents being deformed and oceanic crust 'buckling down'. We have not related such features to Hess's speculation, but you should be able to suggest *two* phenomena that fit in with his ideas.

Hess concluded his paper with the following statement:

> ... the writer has attempted to invent an evolution for ocean basins. It is hardly likely that all the numerous assumptions made are correct. Nevertheless, it appears to be a useful framework for testing various and sundry groups of hypotheses relating to the oceans. It is hoped that the framework, with necessary patching and repair, may eventually form the basis for a new and sounder structure.

The process that Hess thus proposed became known as **sea-floor spreading**. This may be defined concisely as the process by which the lithospheric plates on either side of an ocean ridge grow by the addition of igneous material as they spread apart.

* Metamorphism is the process by which existing rocks are changed deep within the Earth by the effects of heat and pressure. A simple analogy, only involving heat, is the firing of clay to produce bricks and pottery. The process is explained in more detail in Unit 27.

MAGNETIC ANOMALY

LINEAR MAGNETIC ANOMALY

Hess himself did not coin the term 'sea-floor spreading' (even though he described it!). It was coined in 1961 by Robert S. Dietz of the US Navy Electronics Laboratory in California, who used it in a paper published in *Nature* (a widely read weekly scientific journal published in London) that explored the consequences of Hess's ideas for the evolution of mountain belts and ocean basins. At a later date he gave Hess full credit for the concept to which he (Dietz) had given such an attractive name.

As we shall see, Hess's sea-floor spreading idea was confirmed by a variety of independent lines of investigation during the early 1960s, although the simple model of mantle convection which he proposed is now in question (Section 5.4).

4.7 A SEA-FLOOR TAPE RECORDER

During World War II, the need to improve techniques of submarine detection had led to the development of sensitive airborne *magnetometers*, and after the war, devices were designed for towing the instruments behind ships. Magnetometers are very sensitive instruments for detecting extremely small fluctuations in the Earth's total magnetic field. These fluctuations are caused by the tiny amounts of magnetic material present in crustal rocks. A reading obtained by a magnetometer at any point on the Earth's surface is a measure of:

1 the magnetic field produced dynamically in the Earth's outer core; and

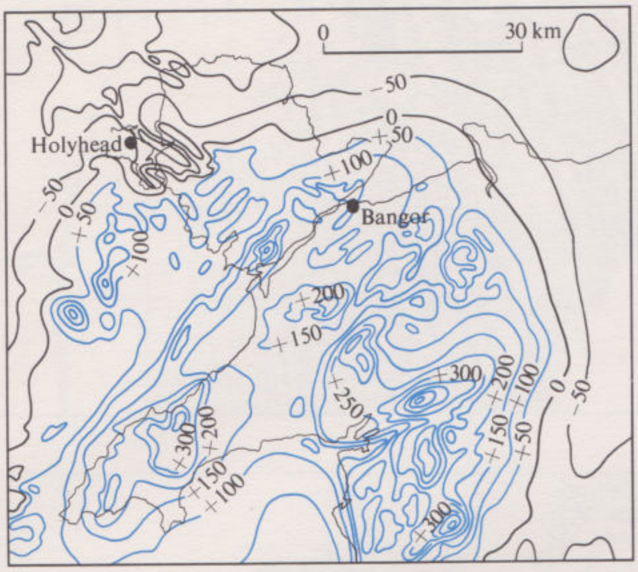
2 small local variations in the total magnetic field caused by magnetic materials present in the crustal rocks.

The internally produced field (item 1) is thought to be the consequence of convection currents in the Earth's outer core (see Units 5–6, Section 4.4.1), whereas the small local variations in the Earth's magnetic field result from the magnetic properties of the cold crust.

It is the small local variations that concern us here. These variations are of between 0.1 and 2.0% of the Earth's total magnetic field, and so they were not discussed when we dealt with magnetism on a global scale in Units 5–6. The maps of the magnetic field in Units 5–6 are on such a scale that variations in the field caused by crustal rocks do not show up; these maps are said to have a *low resolution*, and do not reveal fine detail. However, the local variations are the most useful component of the Earth's magnetic field, for they can be used to help in locating certain rock types buried several kilometres down, or concealed by the oceans. Maps showing the local variations in the Earth's magnetic field after the dipole and non-dipole components have been subtracted show **magnetic anomalies**, the patterns of which offer clues concerning the nature of the underlying rocks. The pattern of magnetic anomalies may reflect both the amount of magnetic material present in the underlying rocks and the orientation of the geomagnetic field at the time when any igneous rocks cooled below their Curie temperatures. Examples of magnetic anomaly maps are shown in Figure 30.

Early surveys in the 1950s showed that the axial rift of the Mid-Atlantic Ridge possessed a marked positive magnetic anomaly, but later, more detailed work showed that ocean basins possessed a remarkably **linear magnetic anomaly** pattern, quite unlike anything seen on continents (compare Figure 30a with Figure 30b).

In 1955, the US Coast and Geodetic Survey began very detailed submarine mapping off the west coast of North America in connection with the development of navigation systems for US nuclear submarines. Despite the top-secret nature of the results of this work, the Survey offered to tow a magnetometer from the Scripps Institute of Oceanography behind their ship, which traversed the Pacific off western North America in a series of east–west tracks spaced at 8 km intervals. The results of the magnetic



(a)

(b)

FIGURE 30 Magnetic anomaly patterns showing variations in the Earth's magnetic field produced by variations in the magnetic properties of crustal rocks. Contour intervals are in gammas (one gamma is 10^{-9} T); contours with positive values are shown in blue. The contours are plotted using observations from which the Earth's total field (about $50\,000 \times 10^{-9}$ T) has been subtracted.

(a) A continental area (North Wales) showing characteristic magnetic anomaly pattern of rounded contour distributions.

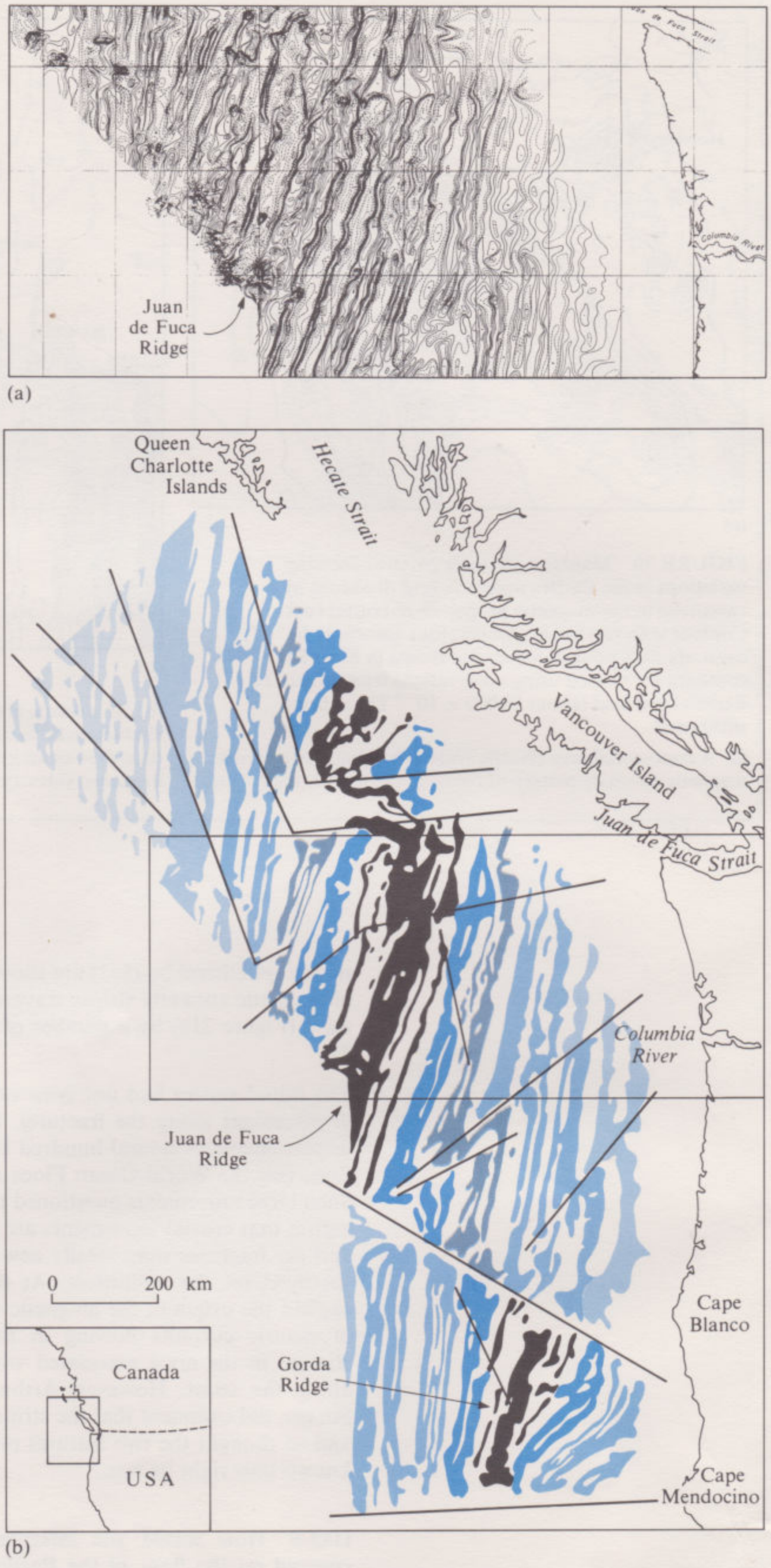
(b) An oceanic area west of California showing characteristic linear magnetic anomaly pattern (often described as magnetic stripe anomalies) which has been displaced sideways by 156 km by a large fault (see Figure 32).

survey (published in 1961) are shown in Figure 31a. They showed a pattern of magnetic anomaly stripes traversing the area and cut and displaced sideways (Figure 31b) by a number of what appeared to be tear faults (Figure 32).

The initial survey had not been extensive enough to reveal the amount of displacement along the fractures, but later surveys showed them to have displacements of several hundred kilometres, with the Mendocino Fracture Zone (see the World Ocean Floor map) having a displacement of 1 100 km. Such large movements questioned the assumption made by continental geologists that crustal movements are predominantly vertical. Both the stripes and the fractures were totally new features, unlike anything that had been surveyed on the continents. At first, oceanographers were at a loss to explain the origin of the magnetic stripes: suggestions ranged from systems of electric currents flowing in the crust, to magnetization induced by stresses in the crust associated with the building of the mountain ranges along the coast. However, Arthur Raff, who had initiated the Scripps Survey, did comment that the stripes seemed to run parallel to ocean ridges, and so thought the two features might be related—at the time, little did he known how right he was.

ITQ 8 How would *you* interpret the striped magnetic anomalies discovered on the floor of the Pacific to the west of the USA and Canada, given that (a) you are already aware of some of Hess's speculations (especially the first one summarized on page 38), and (b) you know from Units 5–6 that the polarity of the Earth's magnetic field suffers periodic reversals? Figure 33 should help your speculations! It is essential that you do not skip reading the answer to this question.

FIGURE 31 Results of magnetic survey carried out off Western North America in 1955 and 1956, published in 1961.



(a) A portion of the survey showing contour pattern of magnetic anomalies. The location of this map is shown by the box in the centre of Figure 31b.

(b) Data covering a larger area than that shown in (a), simplified to show areas where magnetic intensity is higher than average (black or blue—the significance of the use of black and different tones of blue will become apparent in the next few pages), and lower (white). Inferred major displacements are indicated by black straight lines (see Section 4.9).

Note that when these 'magnetic maps' were first published, the locations of the Juan de Fuca Ridge and the Gorda Ridge (both ocean ridges) were not generally known, as the results of bathymetric surveys were still classified information!

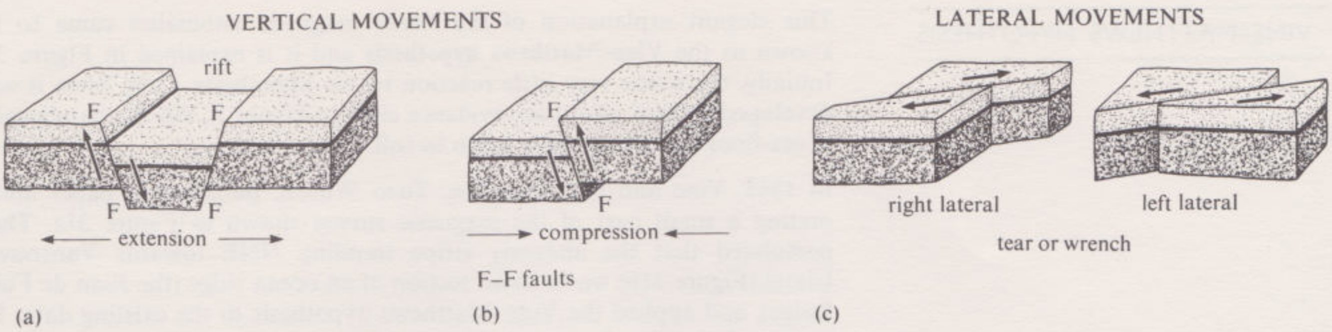
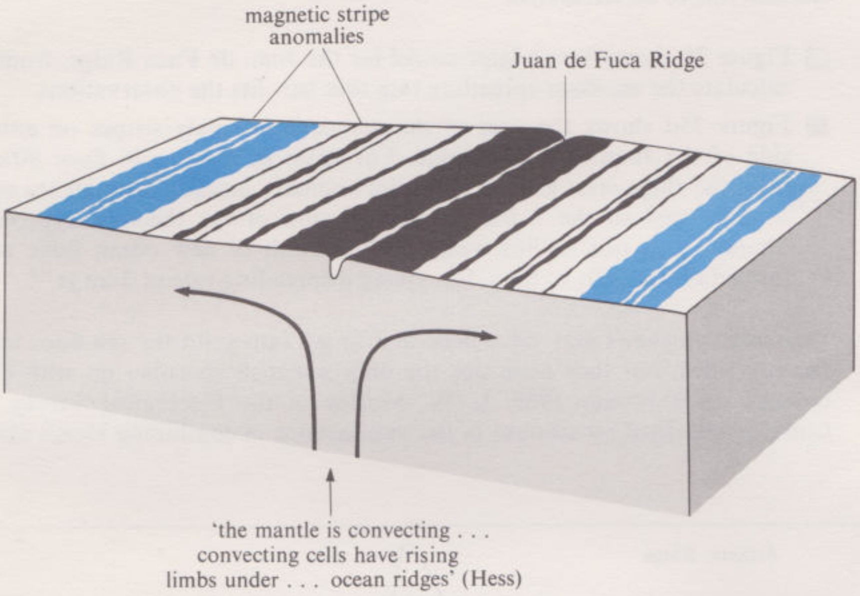


FIGURE 32 Block models illustrating geological faults. Until magnetic surveys of ocean basins revealed many large faults with large sideways or lateral movements, geologists had considered that most faulting involved predominantly vertical movements.



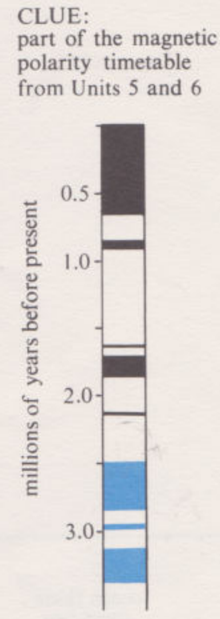


FIGURE 33 A sketch block diagram of part of the sea-floor shown in the box in the centre of Figure 31b, incorporating Hess's speculation that the mantle is convecting, with rising cells under ocean ridges. For use with ITQ 8.

In 1962, Drummond Matthews of the University of Cambridge conducted a very detailed magnetic survey of a small region (just over $600\,\mathrm{km}^2$) of the Carlsberg Ridge in the Indian Ocean (see the World Ocean Floor map). Later that year and early in 1963, Fred Vine, then newly graduated from Cambridge, worked on the data obtained from the Carlsberg Ridge, and in September 1963 published a paper jointly with his supervisor (Matthews) with the rather insignificant-sounding title 'Magnetic anomalies over oceanic ridges'. They wrote as follows:

> Work on this survey led us to suggest that some 50% of the oceanic crust might be reversely magnetized and this in turn has suggested a new model to account for the pattern of magnetic anomalies over the ridges.
>
> The theory is consistent with, in fact virtually a corollary of, current ideas on ocean floor spreading and periodic reversals in the Earth's magnetic field. If the main crustal layer of the oceanic crust is formed over a convective up-current in the mantle at the centre of an oceanic ridge, it will be magnetized in the current direction of the Earth's field. Assuming impermanence of the ocean floor, the whole of the oceanic crust is comparatively young, probably not older than 150 Ma, and the thermoremanent component* of its magnetization is therefore either essentially normal, or reversed with respect to the present field of the Earth. Thus, if spreading of the ocean floor occurs, blocks of alternately normal and reversely magnetized material would drift away from the centre of the ridge and parallel to the crest of it.
>
> This configuration of magnetic material could explain the lineation or 'grain' of magnetic anomalies observed over the Eastern Pacific to the west of North America.

* This is the magnetic field frozen into the ocean crust when it cools past the Curie point of the magnetic materials within it (see Units 5–6).

VINE–MATTHEWS HYPOTHESIS

This elegant explanation of the linear magnetic anomalies came to be known as the **Vine–Matthews hypothesis** and it is explained in Figure 34. Initially, there was very little reaction to the hypothesis. Only when it was developed further, and more evidence cited to favour it, did the bandwagon of sea-floor spreading really begin to roll.

In 1965, Vine and the Canadian, Tuzo Wilson, published a paper interpreting a small part of the magnetic survey shown in Figure 31a. They postulated that the anomaly stripe trending NNE towards Vancouver Island (Figure 31b) was a small section of an ocean ridge (the Juan de Fuca Ridge), and applied the Vine–Matthews hypothesis to the existing data. By now, a timetable of reversals in the polarity of the Earth's magnetic field had been worked out (although not in as much detail as that shown in Units 5–6, Figure 72) and this could be incorporated into the model. The only piece of information missing was the rate of spreading, but their model enabled this to be calculated.

□ Figure 35 shows Vine's later model for the Juan de Fuca Ridge; from it calculate the sea-floor spreading rate that best fits the observations.

■ Figure 35d shows the ages of the magnetic anomaly stripes on either side of the Juan de Fuca Ridge. For example, the ocean floor 90 km from the ridge crest gives a magnetic anomaly profile that matches reasonably well to the 3 million year section of the theoretical profile. Therefore, in one million years, 30 km width of new ocean floor was formed on one side of the ridge, giving a spreading rate of $3\,\text{cm}\,\text{yr}^{-1}$.

Vine and Matthews may have been first to get into print the sea-floor tape recorder idea, but they were not the only scientists to come up with this concept. In February 1963, L. W. Morley of the Geological Survey of Canada submitted an account of the implications of combining Hess's ideas

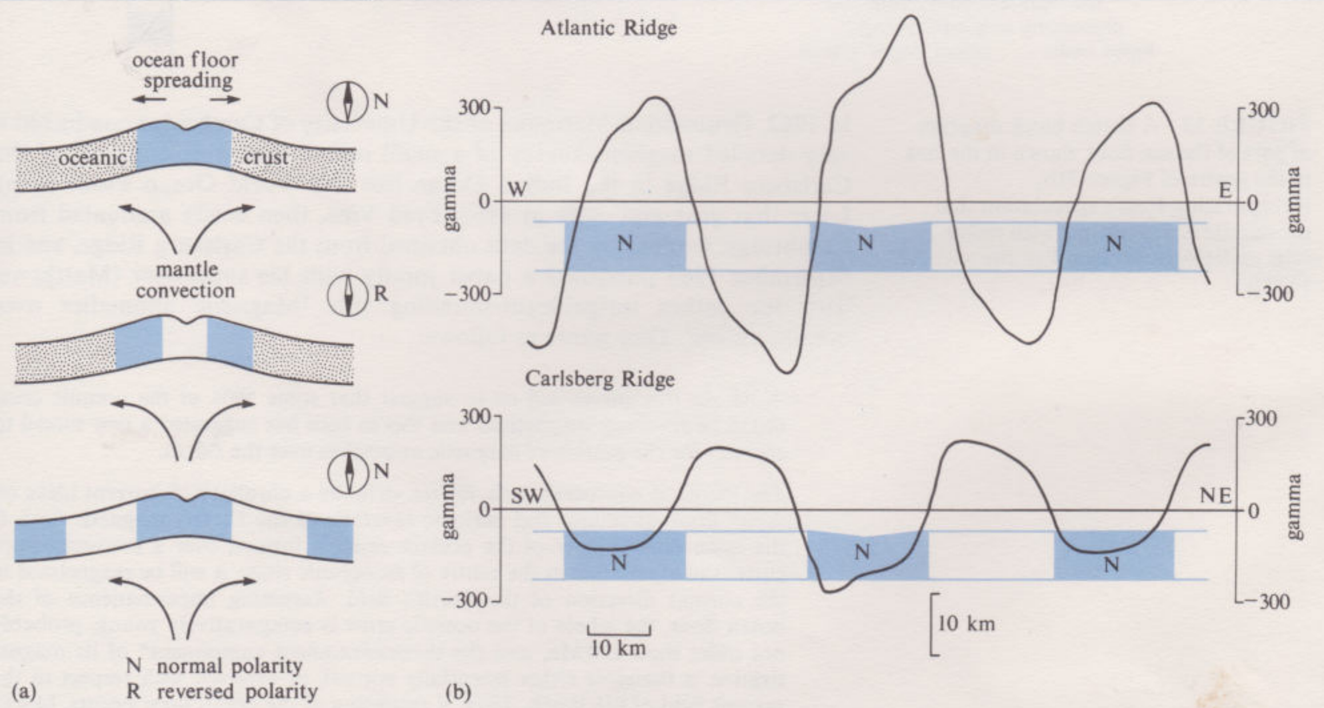


FIGURE 34 (a) The Vine–Matthews hypothesis linked Hess's ideas concerning mantle convection with the new discovery that the Earth's magnetic field suffers periodic polarity reversals. Vine and Matthews assumed that alternate periods of normal and reversed polarity are recorded in ocean-floor rocks during the spreading process.

(b) Using the model depicted in (a), Vine and Matthews were able to compute magnetic profiles that would be produced for the Atlantic and Carlsberg Ridges (one gamma is 10^{-9} T).

The paradox that a negative gamma value over the Carlsberg Ridge is interpreted as being produced by a strip of normally magnetized ocean crust is due to the inclination of the present geomagnetic field being almost zero, and the orientation of the remanent field is nearly parallel to it. The full explanation need not concern you.

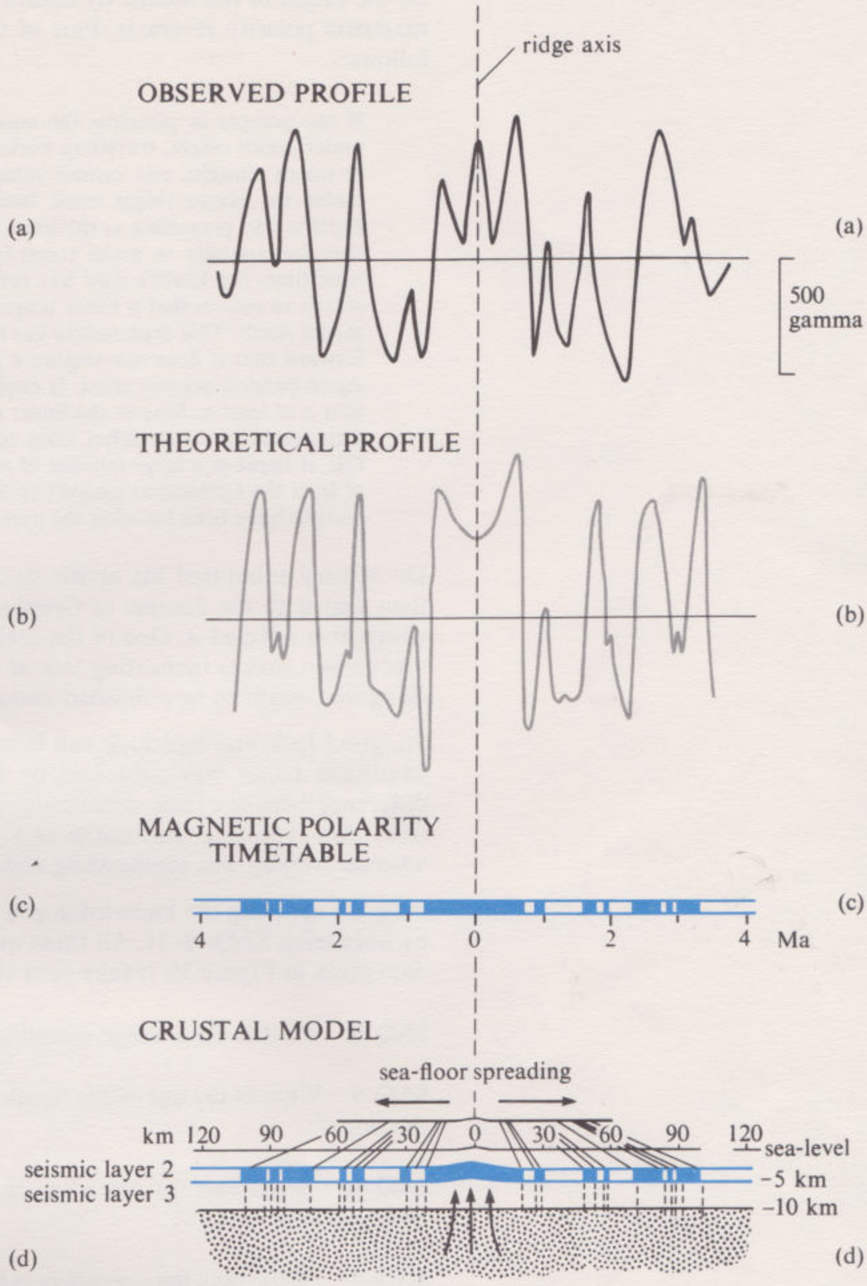


FIGURE 35 Vine's model for the Juan de Fuca Ridge (for location see Figure 31b), first published in 1968. By this time, the timetable of polarity reversals of the Earth's magnetic field back to about 4 million years ago was known. In (c), this 'timetable' is turned on its side and repeated on either side of the ridge axis, to equate with the magnetization of ocean crust, and in (b) it is used to compute a theoretical profile for the Juan de Fuca Ridge. This profile is calculated from knowledge of the Earth's present geomagnetic effect in the region, plus the predicted additional effects of strips of ocean floor alternately showing normal and reversed magnetic polarity.

This theoretical profile compares well with the observed profile (a), providing evidence in favour of the hypothesis that new ocean crust forms over the ridge, and then spreads sideways as a consequence of mantle convection. This being so, the magnetic polarity timetable (c) can be related to the magnetic stripe anomalies observed on either side of the Juan de Fuca ridge (d), and so equated to successive magnetic polarity events (*Note:* The Gilsa event at about 1.6 Ma is too small to show on (c) and (d)). As the ages of the epochs are known from palaeomagnetic studies of accessible lava sequences on continents, these ages can be applied to the sea-floor magnetic stripe anomalies, and a rate of sea-floor spreading calculated. Thus variations in the Earth's magnetic field through time are recorded in sea-floor rocks, much like signals on the magnetic tape of a tape recorder. They are even in stereo, with identical signals recorded on each side of the ridge!

on the origin of the oceans by mantle convection with the new timetable of magnetic polarity reversals. Part of the draft of a paper he wrote read as follows:

> If one accepts in principle the concept of mantle convection currents rising under ocean ridges, travelling horizontally under the ocean floor and sinking at ocean troughs, one cannot escape the argument that the upwelling rock under the ocean ridges must become magnetized in the direction of the Earth's field prevailing at the time. If this portion of rock moves upward and then horizontally to make room for new upwelling material, and if, in the meantime, the Earth's field has reversed, and the same process continues, it stands to reason that a linear magnetic anomaly pattern of the type observed would result. This explanation has the advantage over many of the others put forward that it does not require a petrologically*, structurally, thermally, or strain-banded oceanic crust. It requires a convection cell whose axis of rotation is at least as long as the linear magnetic anomalies, and whose horizontal distance of travel stretches from ocean rise to ocean trough. In addition to this, it requires a large number of reversals of the Earth's magnetic field from at least the Cretaceous period† to the present (since no rocks older than Cretaceous have been found in the ocean basins).

Dr Morley submitted his article to *Nature*, and it was turned down. He then sent it to the *Journal of Geophysical Research* (an American journal), which also rejected it. One of the reviewers of the paper commented: 'Such speculation makes interesting talk at cocktail parties, but is not the sort of thing that ought to be published under serious scientific aegis'.

So, good luck and bad luck can influence scientific success. The Vine and Matthews paper was published by *Nature* in September 1963: the main difference between their contribution and that of Morley's was that they were also reporting the results of a new survey (of the Carlsberg Ridge), whereas Morley was synthesizing and explaining already published data.

Now try applying the knowledge you have gained in the preceding Sections by answering SAQs 8–11. All these questions should be answered using the data given in Figure 36. (Make your calculations using the 'actual' profile.)

SAQ 8 What is the average spreading rate for the South Atlantic?

SAQ 9 What is the age of the South Pacific Ocean Floor 350 km out from the ridge?

SAQ 10 What was the spreading rate of the South Pacific between 0 and 10 Ma ago?

SAQ 11 What was the spreading rate in the South Pacific between 10 and 30 Ma ago?

You will have gathered from these exercises that:

1 examination of anomaly profiles provides a means of dating the sea-floor (without taking samples from it and dating them);

2 there are variations in the rates of sea-floor spreading between oceans, and through time.

However, these conclusions are based on the assumption that sea-floor spreading proceeded at a constant rate of $1.8\,\mathrm{cm\,yr^{-1}}$ in the South Atlantic. Critics of the sea-floor spreading hypothesis thought this assumption went too far on the available evidence.

* 'petrologically ... strain-banded oceanic crust' means crust whose rock composition changes laterally, rather than staying as uniform basalt. ('Petrology' is the study of rocks; 'petros' is Greek for rock.)

† As you will see in Units 28–29, geological time is divided into segments, which are given different names. The Cretaceous period ended about 70 Ma ago, and began about 135 Ma ago.

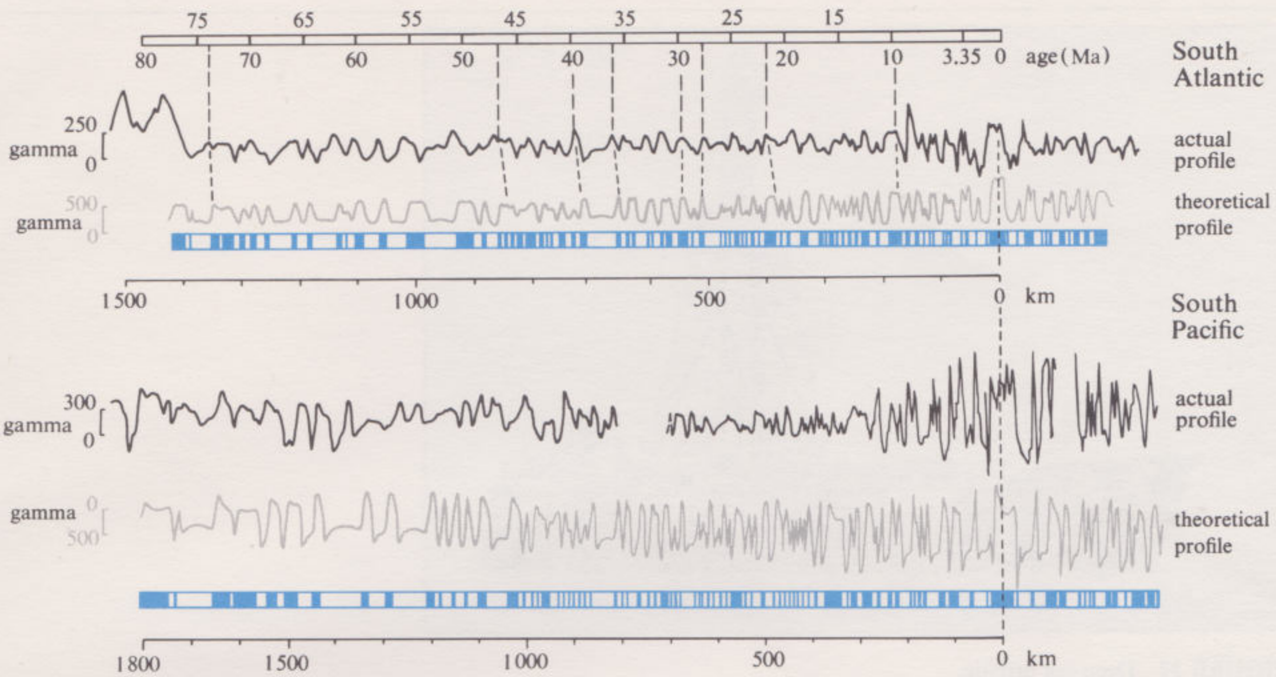


FIGURE 36 Magnetic anomaly profiles across the western flanks of the ocean ridges in the South Atlantic and South Pacific. The spreading rate in the South Atlantic is assumed to be constant so that the age of the ocean floor beyond one hundred or so kilometres from the ridge crest can be determined by extrapolation. Thus 1 400 km from the crest the ocean floor is interpreted to be 77 Ma old. In this way, the magnetic reversal timetable has been extended back in time beyond 4 Ma ago—the original limit that was possible using measurements from continental lava sequences (see Units 5–6, Figure 71). For the South Pacific the observed profiles are compared with computed profiles that assume the same sequence of reversals of the Earth's magnetic field but variations in spreading rate.

☐ What kind of evidence might prove the assumption to be correct?

■ If the ocean floor could be sampled (and so dated by direct measurements) at points where the 'anomaly age' was known, the Vine–Matthews hypothesis could be subjected to an independent check.

4.8 DEEP-SEA DRILLING

In 1957, Harry Hess and a number of other distinguished US scientists suggested that an attempt should be made to drill a borehole deep enough to penetrate the Mohorovičić discontinuity (see Units 5–6, Section 4.5.2). The 'Mohole project', as it became known, opted to take the short-cut route to the Moho, through the ocean floor, where it lies a 'mere' 7 km down, in contrast to the 30 km or greater depth under the continents. The story behind the project is a fascinating one; it took place at a time when there was great rivalry between US and USSR scientists, and for a while there was a feeling that there was a 'race to the mantle', but this turned out to be unfounded. In the end, the project foundered because of escalating costs, accusations of political 'bribery' on the part of the main contractor, and doubts about the wisdom of spending so much money on a single attempt to reach the mantle. In August 1966, the project was terminated, but the money spent on it ($25 million) was not all wasted, for a new technology for drilling in very deep water had been developed. This technology provided the basis for the Deep-Sea Drilling Project (DSDP), which was organized under the auspices of JOIDES (Joint Oceanographic Institutions for Deep-Earth Sampling), a consortium of five oceanographic institutions in the USA. A specially designed ship, the *Glomar Challenger*, was launched in 1968 and operated continuously from July of that year (Figure 37). The original project has been extended with international participation; it is now known as the Ocean Drilling Programme (ODP) and uses a new ship, the *Joides Resolution.*

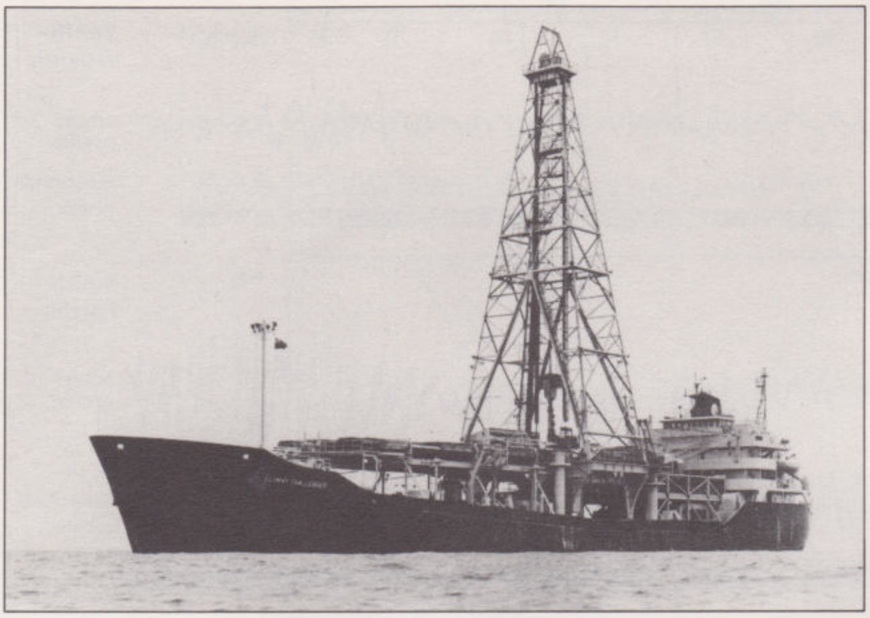
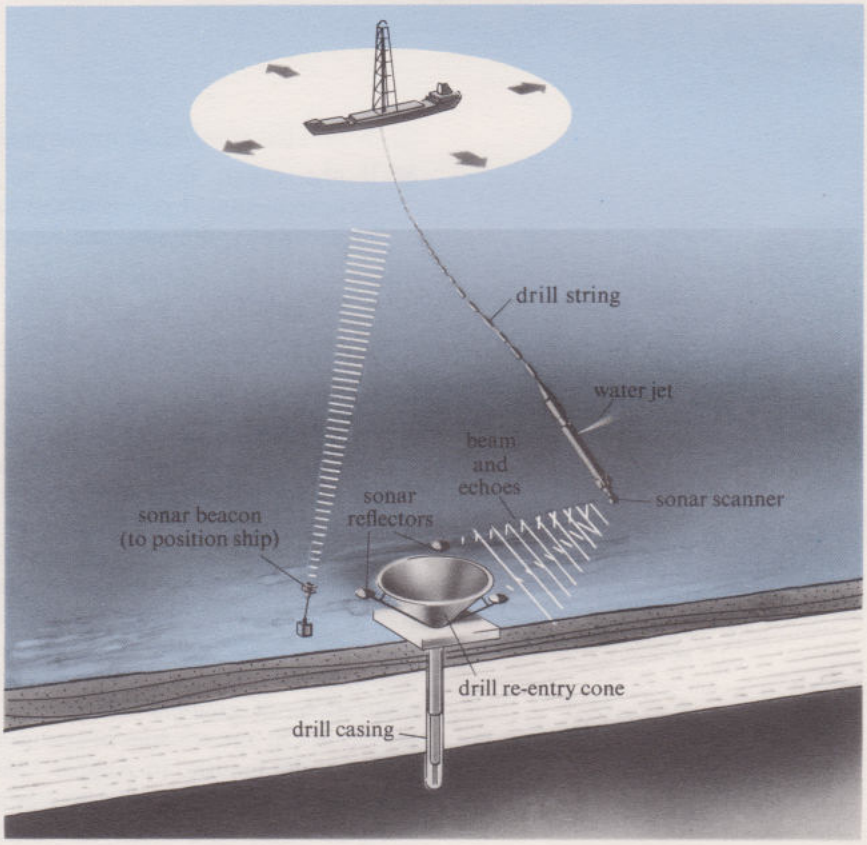


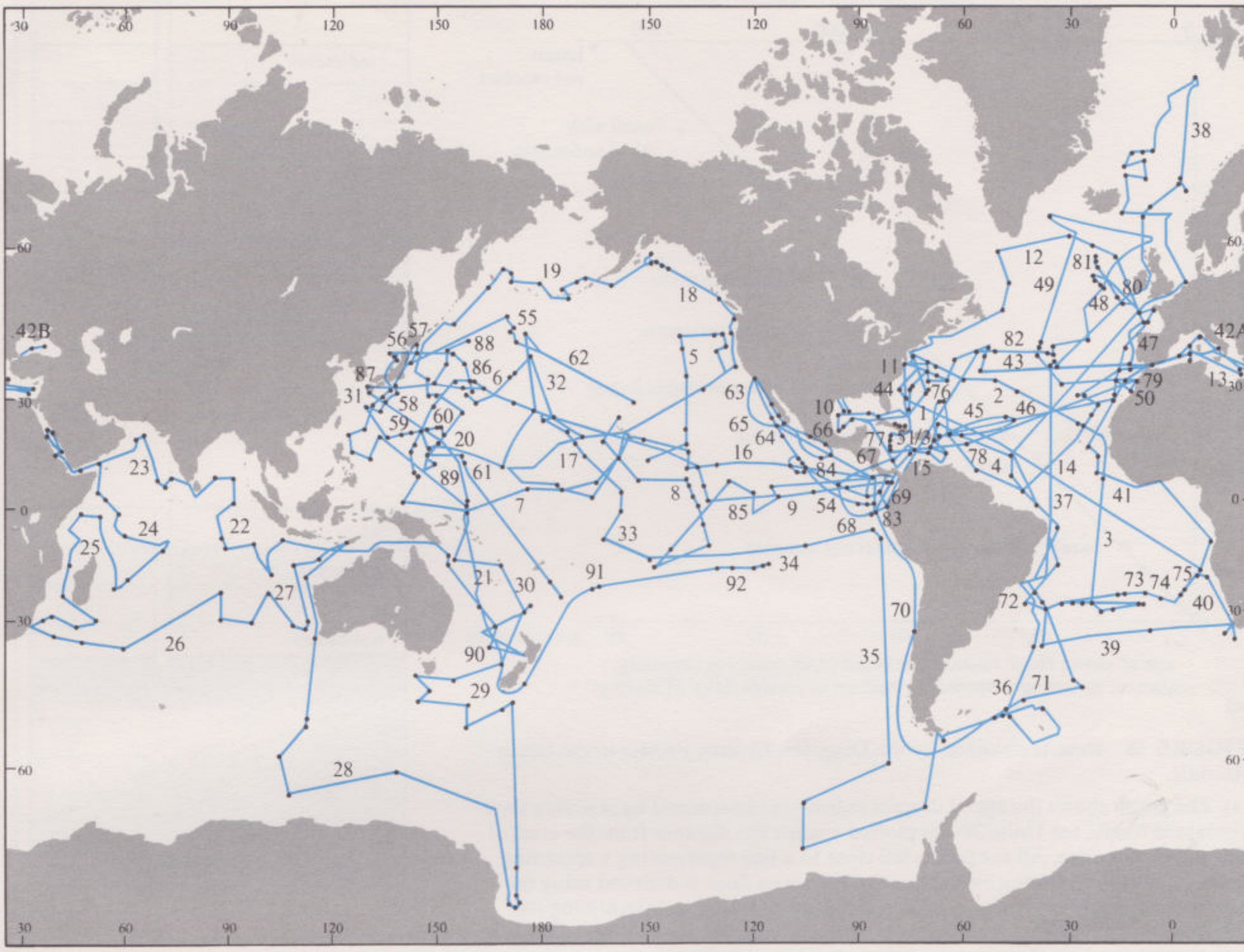
FIGURE 37 Deep-sea drilling.

(a) The *Glomar Challenger*. Thrusters in the bow and stern of the ship were controlled by computer to maintain it within 30 m of a point directly above an electronic beacon previously dropped to the bottom. Drilling thus proceeded without danger of breaking the drill string (many lengths of drill pipe attached to the drill bit).



(b) The drilling system. The re-entry cone is attached to the drill string as it is first lowered to the bottom. The cone remains on the bottom when the drill string is withdrawn for the drill bit to be replaced. For re-entry the drill string is lowered, with the attached sonar scanner providing information about the position of the drill bit assembly so that the water jet can be used to steer the bit into the cone. Before 1970, the *Glomar Challenger* operated without the re-entry system, and so the depth of holes drilled was limited by the life of a single drill bit.

FIGURE 37 continued



(c) Routes covered by DSDP and ODP during August 1968–March 1983. Numbers refer to 'legs', which are cruises of about two months duration, during which an average of ten sites (each shown as a dot) are drilled.

One of the first tasks of the *Glomar Challenger* was to test the sea-floor spreading hypothesis. In early 1969 on the ship's third cruise, a number of holes were drilled at sites on either side of the Mid-Atlantic Ridge in the South Atlantic. Basalt was retrieved from most of these holes, and it was dated by using fossils to determine the age of the overlying sediments.

□ On the basis of the previous discussion concerning rates of sea-floor spreading, and the answer to SAQ 8, would you expect a graph of the age of the sample plotted against its distance from the ocean ridge to show the points falling along a curve, along a straight line, or randomly?

■ If the sea-floor spreading rate in the South Atlantic had remained constant throughout its opening, the points on such a graph would fall along a straight line, *provided* that true ocean floor had been sampled (see Figure 38 for further discussion).

The results shown in Figure 38 confirmed the hypothesis of sea-floor spreading *and* the constant rate of spreading postulated for the South Atlantic.

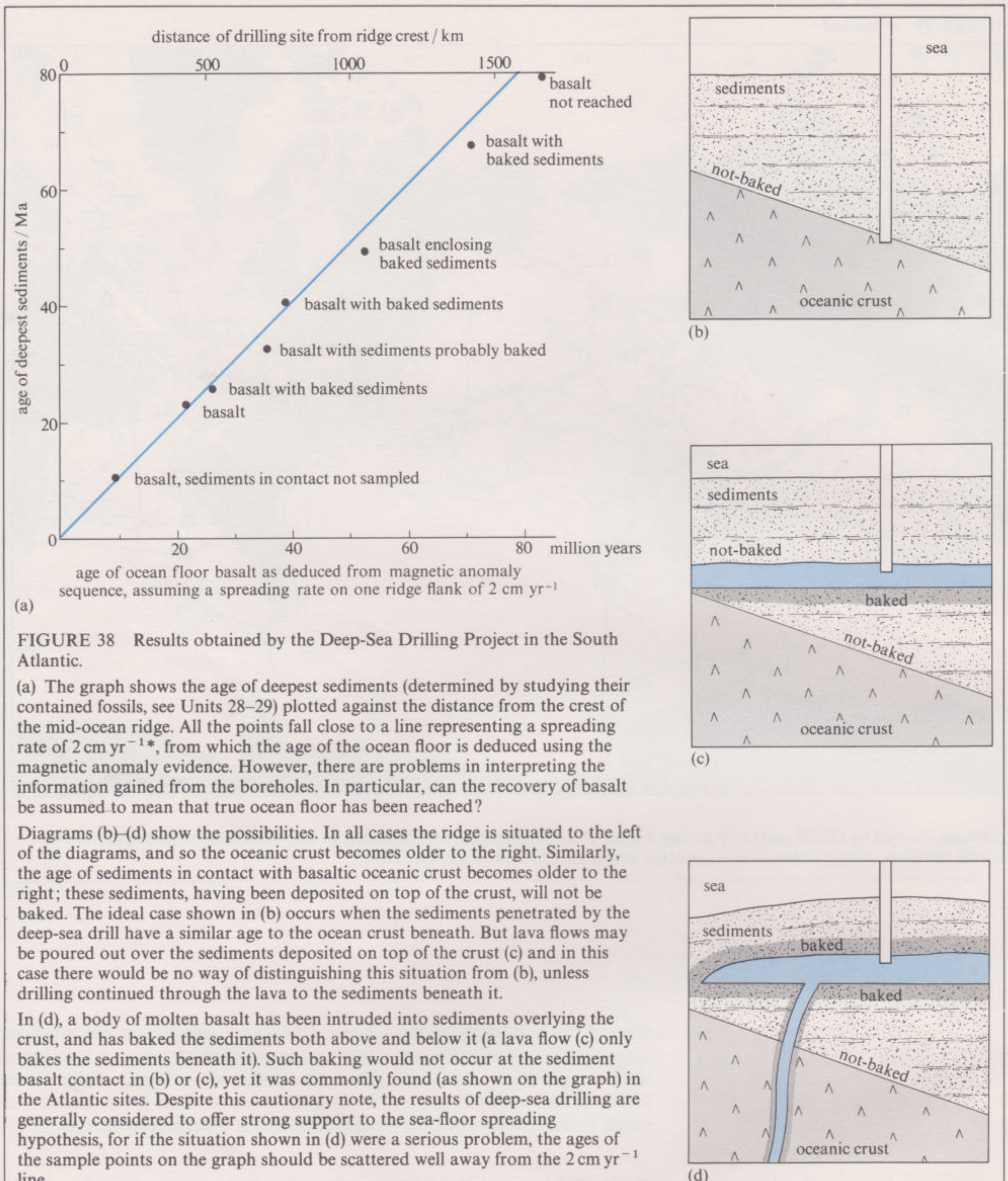


FIGURE 38 Results obtained by the Deep-Sea Drilling Project in the South Atlantic.

(a) The graph shows the age of deepest sediments (determined by studying their contained fossils, see Units 28–29) plotted against the distance from the crest of the mid-ocean ridge. All the points fall close to a line representing a spreading rate of 2 cm yr^{-1}*, from which the age of the ocean floor is deduced using the magnetic anomaly evidence. However, there are problems in interpreting the information gained from the boreholes. In particular, can the recovery of basalt be assumed to mean that true ocean floor has been reached?

Diagrams (b)–(d) show the possibilities. In all cases the ridge is situated to the left of the diagrams, and so the oceanic crust becomes older to the right. Similarly, the age of sediments in contact with basaltic oceanic crust becomes older to the right; these sediments, having been deposited on top of the crust, will not be baked. The ideal case shown in (b) occurs when the sediments penetrated by the deep-sea drill have a similar age to the ocean crust beneath. But lava flows may be poured out over the sediments deposited on top of the crust (c) and in this case there would be no way of distinguishing this situation from (b), unless drilling continued through the lava to the sediments beneath it.

In (d), a body of molten basalt has been intruded into sediments overlying the crust, and has baked the sediments both above and below it (a lava flow (c) only bakes the sediments beneath it). Such baking would not occur at the sediment basalt contact in (b) or (c), yet it was commonly found (as shown on the graph) in the Atlantic sites. Despite this cautionary note, the results of deep-sea drilling are generally considered to offer strong support to the sea-floor spreading hypothesis, for if the situation shown in (d) were a serious problem, the ages of the sample points on the graph should be scattered well away from the 2 cm yr^{-1} line.

* This value differs from that given in the answer to SAQ 8 because the rate of sea-floor spreading in the South Atlantic increases from north to south; the reason for this will become apparent in Section 4.10. The data plotted in Figure 38a were obtained from samples obtained slightly further south than the magnetic anomaly traverse shown.

TRANSFORM FAULT

4.9 TRANSFORM FAULTS

In Section 4.7 we showed how oceanic magnetic anomalies revealed that geological faults with large lateral displacements are common features of oceanic crust. This contrasts with faults cutting continental crust, which mostly show vertical movement.

□ Examine Figure 32 (p. 43) once more. Would you expect Earth movements along tear faults to produce earthquake epicentres all along the length of the fault, or just along one sector of it?

■ As one crustal slab is sliding past another, over a period of time, earthquake epicentres should occur along the whole length of the fault.

□ Now locate on the World Ocean Floor map the following large faults in the Atlantic, which are similar to those we have already examined in the eastern Pacific (Figure 31):

(a) In the North Atlantic, to the south and north of Newfoundland, the Oceanographer Fracture Zone, and the Gibbs Fracture Zone;

(b) In the central (equatorial Atlantic) the Vema, Romanche, Ascension and Rio Grande Fracture Zones.

Once you have located these fracture zones, some of which displace the Mid-Atlantic Ridge by as much as 500 km, decide whether they show the kind of earthquake epicentre distribution you would expect along a major tear fault (i.e. along their entire lengths) by examining Figures 10 and 11 on the fold-out pages at the end of these Units.

■ You were probably surprised to find that the earthquake epicentres are *not* distributed along the entire lengths of these fracture zones or faults, but are confined to the axial region of the Mid-Atlantic Ridge. This suggests that movement is taking place only along a very small part of the fault.

Figures 10 and 11 are not drawn on a large enough scale for the distribution of earthquakes along fracture zones to be described accurately. More detailed maps show that earthquake activity is confined to the region of the fault between the offset portions of ocean ridge, as shown in Figure 39.

ITQ 9 What mechanism could account for earthquake epicentres being confined to the region along a fracture zone between the offset portions of an oceanic ridge? To answer this question, draw a series of arrows on Figure 39 to represent the direction of sea-floor spreading.

In 1965, Tuzo Wilson offered the explanation given in the answer to ITQ 9, and termed these structures **transform faults**. He called them this because, although they show great lateral displacements, they terminate abruptly at both ends, and are transformed into a different structure—an ocean ridge (as in the case illustrated in Figure 39) or an ocean trench.

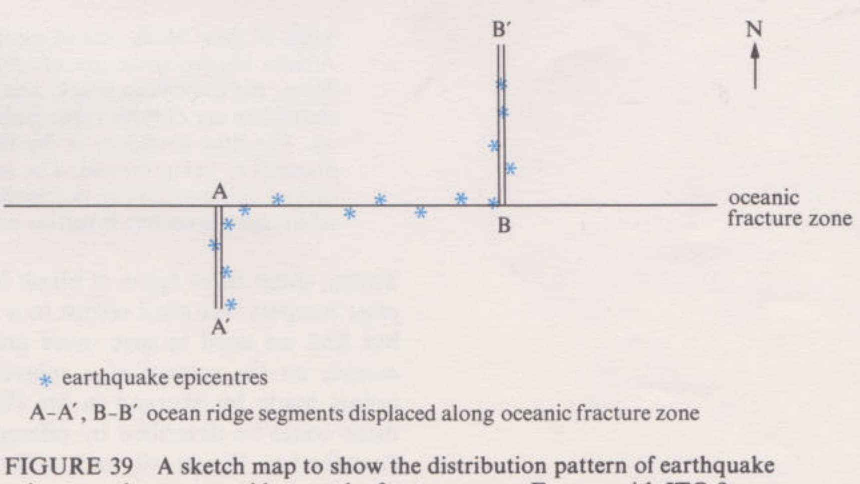


FIGURE 39 A sketch map to show the distribution pattern of earthquake epicentres along ocean ridges cut by fracture zones. For use with ITQ 9.

A good example of one structure transforming into another can be seen in the Western Pacific. Look at the World Ocean Floor map; locate the Fiji Islands to the north of New Zealand. To the west lies the New Hebrides Trench, and to the east the Kermadec–Tonga Trench. The two trenches are linked by a transform fault: the New Hebrides Trench is transformed into the fault, and to the east the fault is transformed back into a trench.

Confirmation of the existence of this new class of faults was first announced in 1966 after studies of earthquakes along the faults, which were made possible by the world-wide network of standardized seismographs that had been set up for the International Geophysical Year in 1957–8. Analyses of seismic shocks emanating from Wilson's postulated transform faults show the movements that would be expected from opposing directions of sea-floor spreading, rather than those suggested by the offsets of the ocean ridges. So, as well as supporting the transform-fault hypothesis, the earthquake data provided yet more support for the sea-floor spreading hypothesis.

4.10 GLOBAL TECTONICS

From 1966 onwards there was a veritable explosion of papers describing the existence of sea-floor magnetic anomaly profiles that confirmed the Vine–Matthews hypothesis. In 1966 Vine published a paper, 'Spreading of the ocean floor: new evidence', whose title no longer coyly concealed the sea-floor spreading ideas, as his 1963 paper with Matthews had done (with the innocent heading 'Magnetic anomalies over ocean ridges'). Thus in less than five years the climate of scientific opinion had completely changed from sceptism to enthusiasm. And, while more evidence poured in from the oceans, other workers showed how the concept of sea-floor spreading could be extended to explain most of the major features of the Earth's crust.

In 1967, D. P. McKenzie and R. L. Parker (both ex-Cambridge geophysicists) then working at the University of California at San Diego, published a paper in *Nature* entitled 'The North Pacific: an example of tectonics on a sphere'. They suggested that data concerning sea-floor spreading, transform faults and island arcs could be explained 'if the sea-floor spreads as a rigid plate, and interacts with other plates in seismically active regions ...'. They suggested that the rigid plates are aseismic areas (that is, they show virtually no seismic activity) and that they move like curved paving stones on the surface of a sphere.

The following year, W. Jason Morgan of Princeton University published a paper entitled 'Rises, trenches, great faults and crustal blocks'. He suggested what he called 'a geometrical framework with which to describe present-day continental drift'. His approach was an extension of Tuzo Wilson's transform fault concept, applied to a spherical surface. He suggested that the surface of the Earth is divided into about 20 blocks:

> Some of these blocks are of continental dimensions (the Pacific block and the African block); some are of sub-continental dimensions (the Juan da Fuca block, the Caribbean block, and the Persian block). The boundaries between the blocks are of three types and are determined by present day tectonic activity. The first boundary is the rise [ocean ridge] type at which new crustal material is being formed. The second boundary is the trench type at which crustal surface is being destroyed ... The third boundary is the fault type at which crustal surface is neither created or destroyed.

Today, these three types of block boundaries are called *plate boundaries* or *plate margins*. We shall return to a detailed discussion of these in Section 5, but first we need to give more attention to the idea of *lithospheric plates moving on the surface of a sphere*—this was one of the most significant points made by Morgan in his 1968 paper. He discussed how this movement could be described by reference to a *pole of rotation*. This concept is described in Figure 40, and is illustrated also in the first TV programme 'Drifting continents'.

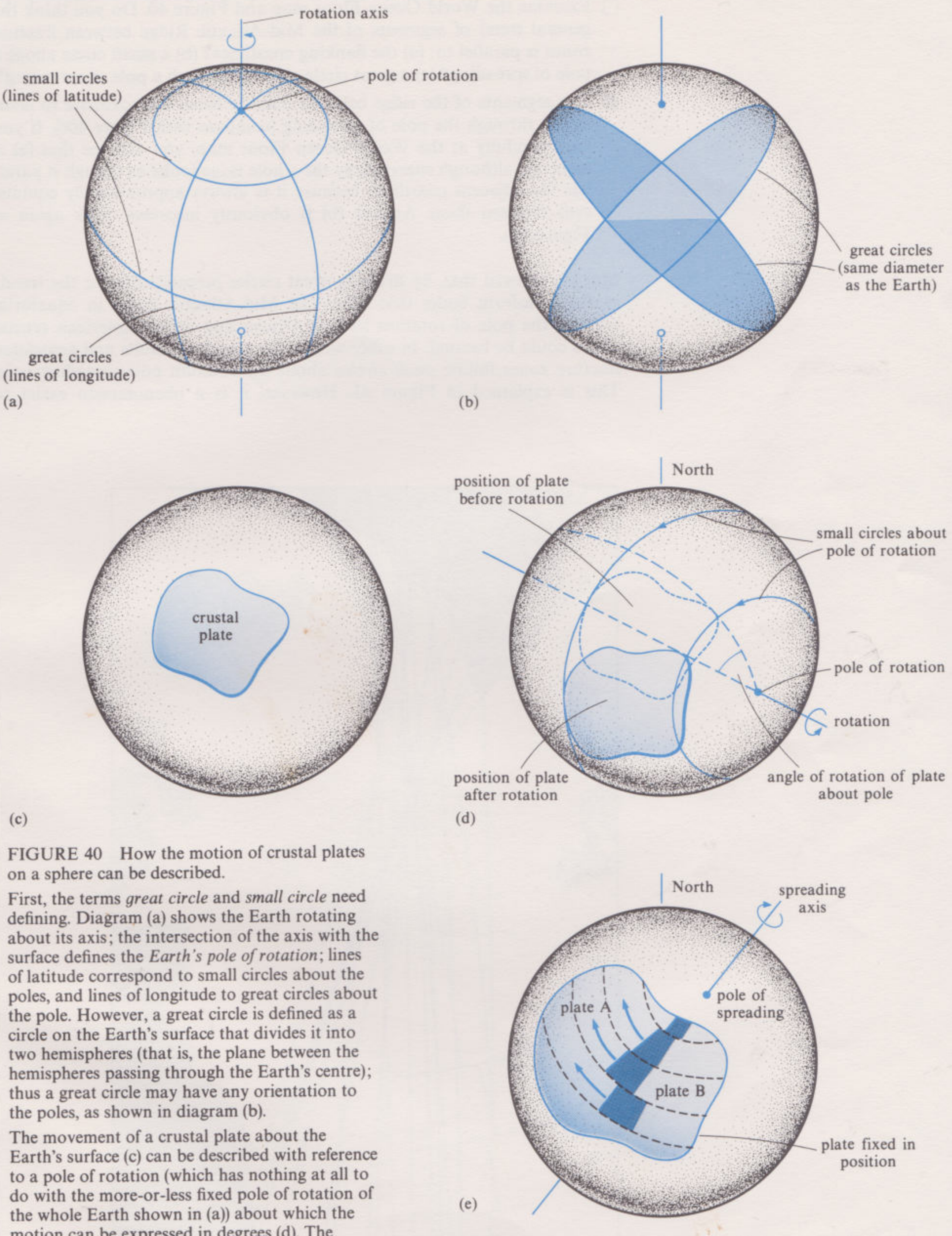


FIGURE 40 How the motion of crustal plates on a sphere can be described.

First, the terms *great circle* and *small circle* need defining. Diagram (a) shows the Earth rotating about its axis; the intersection of the axis with the surface defines the *Earth's pole of rotation*; lines of latitude correspond to small circles about the poles, and lines of longitude to great circles about the pole. However, a great circle is defined as a circle on the Earth's surface that divides it into two hemispheres (that is, the plane between the hemispheres passing through the Earth's centre); thus a great circle may have any orientation to the poles, as shown in diagram (b).

The movement of a crustal plate about the Earth's surface (c) can be described with reference to a pole of rotation (which has nothing at all to do with the more-or-less fixed pole of rotation of the whole Earth shown in (a)) about which the motion can be expressed in degrees (d). The circles shown on (d) are small circles about the pole of rotation, and are parallel to the direction of movement of the plate. Sea-floor spreading can also be described using a pole of rotation, as in (e), by holding one crustal plate fixed. Although the amount of opening expressed in degrees is the same all along the length of the spreading axis, the spreading rate in centimetres per year *increases* away from the pole up to an angular distance of 90° (at the spreading equator) after which it diminishes once more.

☐ Examine the World Ocean Floor map and Figure 40. Do you think the general trend of segments of the Mid-Atlantic Ridge between fracture zones is parallel to: (a) the flanking coastlines? (b) a small circle about a pole of spreading? (c) a great circle passing through a pole of spreading?

■ The segments of the ridge between fracture zones approximate to *great circles* through the pole of spreading (compare with Figure 40e). If you look carefully at the World Ocean Floor map, you will see that (a) is incorrect although superficially the whole ridge looks as though it parallels the adjacent coastlines because it is always approximately equidistant between them. Answer (b) is obviously incorrect; look again at Figure 40e.

Morgan showed that, by drawing great circles perpendicular to the trends of the transform faults that offset the Mid-Atlantic Ridge in equatorial regions, the pole of rotation for the African and South American crustal plates could be located. In other words, the transform faults and associated fracture zones follow *small circles* about the rotation pole/spreading pole. This is explained in Figure 41. However, it is a phenomenon easier to

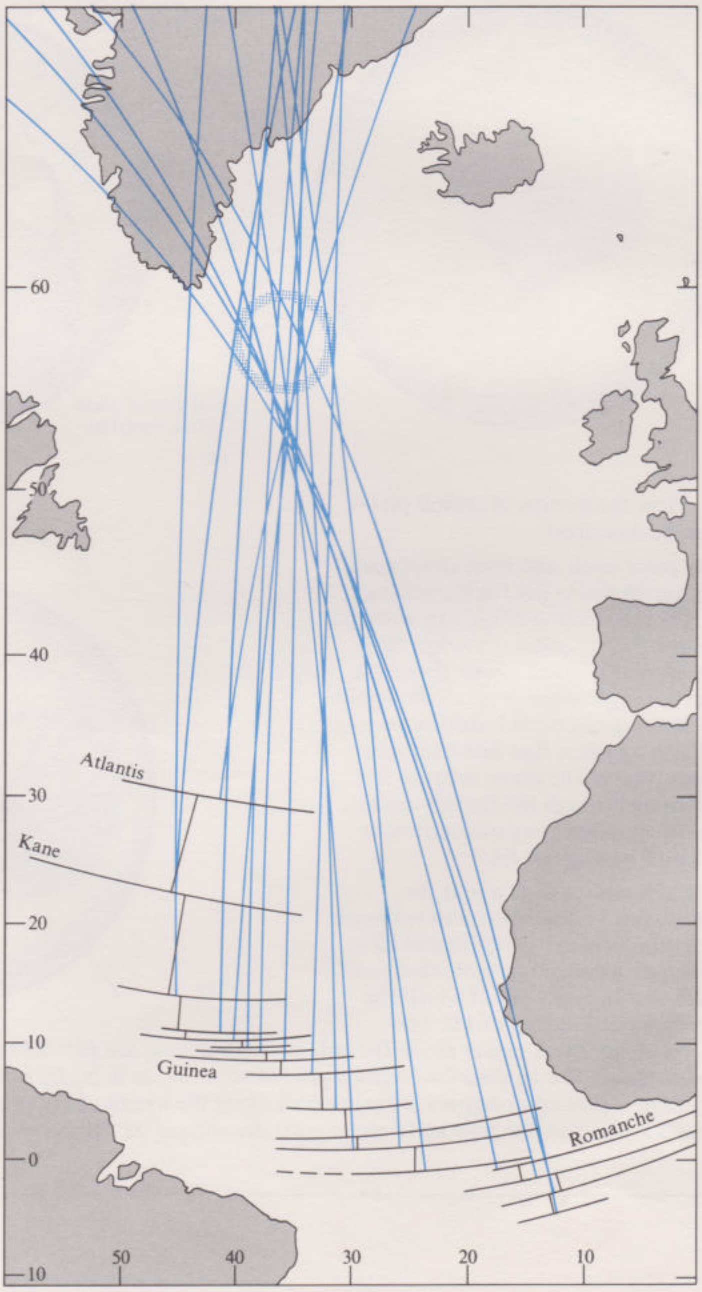


FIGURE 41 The pole of rotation for the African and South American crustal plates located by drawing great circles perpendicular to equatorial Atlantic fracture zones. With one exception, all the lines pass within the circle shown.

demonstrate on a sphere than by using the World Ocean Floor map, and so it is demonstrated in the TV programme 'Drifting continents'.

This analysis of the movements of crustal blocks around the surface of a sphere—spherical geometry—involves sophisticated three-dimensional trigonometry, which need not concern us here. However, you should have grasped the basic principles that underly the analysis (summarized in Figures 40 and 41), and realize that spherical geometry is a powerful tool for integrating data concerning plate movements. Several such integrations were published in 1968, as well as that by Morgan. Xavier Le Pichon, a French oceanographer then working at the Lamont Geological Observatory in New York State, published a paper that extended Morgan's analysis to include a comprehensive survey of all sea-floor magnetic anomaly data, and the location of oceanic fracture zones that were known at that time. His model was reduced to a number of major rigid blocks, and on it he showed the rate of differential movement he had calculated on the basis of known rates of sea-floor spreading and the location of the rotation poles for each block. A more recent version of this map is shown in Figure 42.

□ Figure 42 shows South America flanked by two ocean ridges which, as you read earlier, are both spreading at rates of several centimetres per year. But these two spreading centres are spreading towards each other. Do you remember Hess's speculation on how this apparent excess of crust formation was accommodated?

■ He suggested that oceanic crust plunges beneath the continents. Figure 42 shows that the South American and Nazca Plates are colliding with each other along the region of the trench off the west coast of South America.

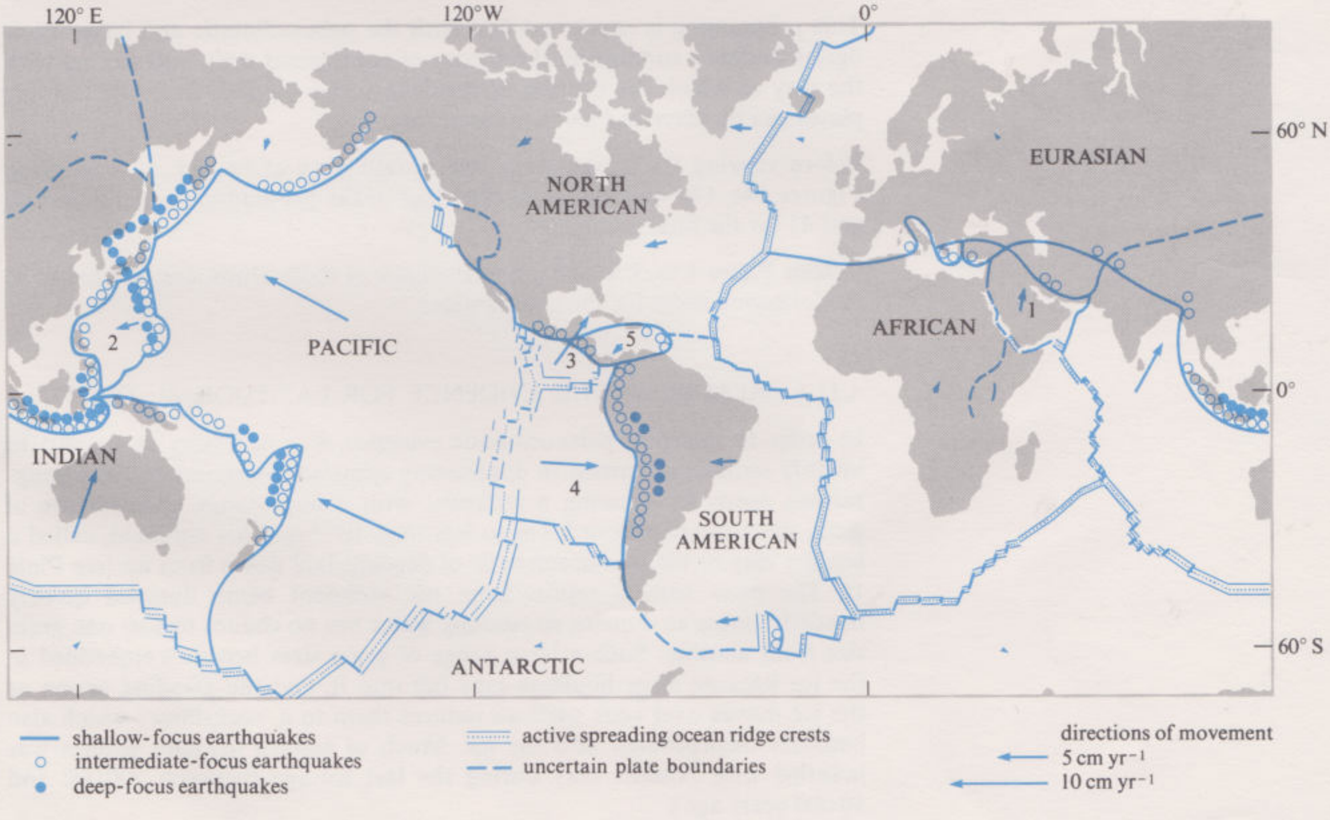


FIGURE 42 The distribution of lithospheric plates and the seismicity at their boundaries. All the plate boundaries are regions of shallow seismicity; deeper-focus earthquake zones mark the sites of destructive plate boundaries. Spreading rates at constructive plate boundaries are shown schematically by the width between the parallel lines used to show them. The directions of plate movement are shown by arrows; the lengths of which are proportional to the rate of movement: the shorter the arrow, the slower the plate is moving. Because the plates move over certain thermal features in the asthenosphere, which we can assume are fixed, the directions of the plate movements can be calculated. These directions are known as absolute plate motions. The seven major plates are named. Minor plates are numbered as follows: 1 Arabian; 2 Philippine; 3 Cocos; 4 Nazca; 5 Caribbean.

SUBDUCTION
BOULDER CLAY
TILL

□ Do you remember what Wadati–Benioff zones are? (If not, turn to Section 4.4.5 and refresh your memory). How do they fit into this picture of crustal plates growing and colliding?

■ These inclined zones of earthquakes mark the sites at which slabs of ocean crust are plunging down into the mantle; this process is called **subduction.**

Just as the existence of the new class of geological faults, namely transform faults, had been confirmed by detailed studies of earthquakes with epicentres along their length, so was the concept that blocks of crust were jostling each other on the surface of a sphere. Yet another 1968 paper, also from Lamont, written by Bryan Isacks, Jack Oliver and Lynn Sykes, gave strong support to what they termed the 'new global tectonics' (now generally called *plate tectonics*).

Their interpretation, based on a global analysis of earthquakes, confirmed Le Pichon's view of the movements of the major blocks. Moreover, the three authors added a third dimension, namely depth, and showed that the earthquake data confirmed the view that ocean crust was indeed plunging downwards (was being subducted) along Wadati–Benioff zones, confirming the interpretation based on earthquake epicentre depths, gravity anomalies and heat-flow measurements.

Thus, by 1968, a wide variety of geological and geophysical observations had been integrated into one global theory, that of plate tectonics. In Section 5 of these Units we shall outline in more detail some of the processes that occur where plates are formed, and where they collide.

4.11 DRIFTING CONTINENTS (TV PROGRAMME)

This programme is concerned first with the palaeoclimatic and palaeontological evidence supporting the theory of continental drift, and second with the way in which the drifting of continents and the movement of tectonic plates can be described using poles of rotation.

Before viewing the programme you should have examined, at least once, Figures 14c, 14d and 19 for the first half of the programme and Figures 40 and 41 for the final section.

Colour Plates 1 to 5, which are at the back of these Units, are referred to in the following notes for the programme.

4.11.1 PALAEOCLIMATIC EVIDENCE FOR LATITUDINAL DRIFT

In order to interpret palaeoclimatic evidence, it is necessary to be able to identify sediments formed in contrasting climatic environments. The programme opens by showing a sediment with a huge range and mixture of grain sizes, ranging from 0.3 m to less than 10^{-6} m. This sediment, called a **boulder clay** or **till**, is characteristic of deposits laid down from ice (see Plate 1). The poor sorting results from the sediment being dumped quickly beneath the ice as it melts, so running water has no chance to sort one grain size from another. Such a large range of grain sizes becomes embedded in the ice because large boulders may fall into it, and the grinding action as the ice moves over rock surfaces reduces them to a 'rock-flour', which also becomes incorporated into the ice. Much of eastern lowland Britain was mantled with boulder clay during the last ice age (between 200 000 and 10 000 years ago).

The boulder clay shown at the beginning of the programme can be seen in the bottom left of Plate 2, and it overlies the coal seam being worked in this Durham open-cast site. (Note how the debris has to be excavated and removed from the old workings of some 200 years ago.) On the right of the picture is a vertical face of sandstone and shale (which was once mud), and behind the mechanical shovel are two coal seams. The upper coal seam,

which is one metre thick, was once uncompacted, rotting vegetation almost ten times as thick as it is now. Evidence that this material accumulated beneath swampy forests comparable to the present-day tropical rain-forests includes fossil plant leaves and stems from coal-bearing strata (Plate 3). Thus Britain's coalfields are evidence that the country was once situated in an equatorial region. Fossil trees from a preserved fossil grove on display in Victoria Park Glasgow grew to a height of over 30 m. The shape of their root systems is similar to those of trees growing in swampy conditions at the present time.

The simplified map used in the programme (Plate 4) shows the distributions of both hot, wet (i.e. tropical rain-forest) areas, and hot, dry areas on the Earth today. Hot, dry areas contain a number of sediment types that characterize such conditions, and that if found as 'fossils' would be good palaeoclimatic indicators. Among these are the desert sand dunes shown during the programme. These dunes are made up of extremely well-rounded sand grains, which are almost all the same size (i.e. they are very well sorted), and the migration of the dunes produces a characteristic cross-bedding structure, the formation of which is illustrated in Figure 43.

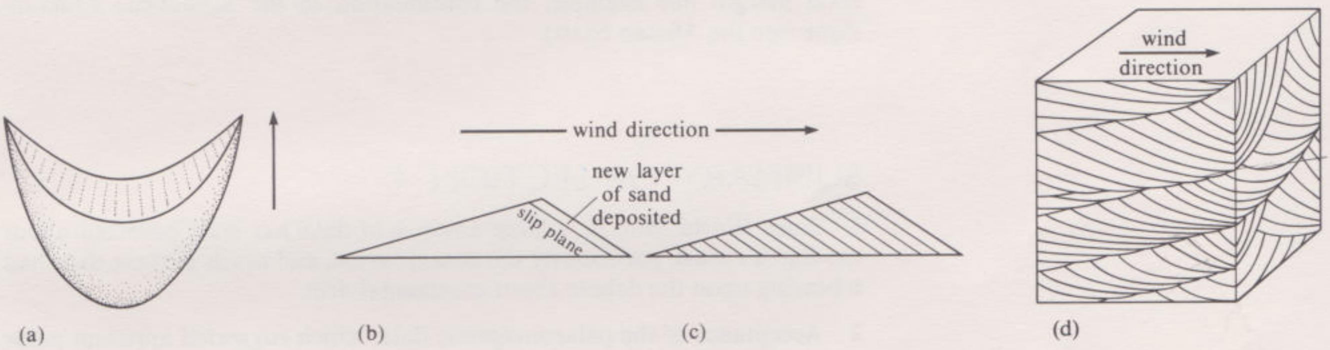


FIGURE 43 (a) Plan view of crescent-shaped sand dune with steep face inclined in the down-wind direction. (b) and (c) Cross-sections through sand dune shown in (a) taken in plane parallel to wind direction, to show how new layers of sand are deposited on the down-wind side. (d) Diagram of the three-dimensional structure of the sand layers that would accumulate from a series of sand dunes similar to that shown in (a).

The cross-bedding of sands from Durham that are 270 Ma old shows up clearly in Plate 5. The nature of the sand grains (well-rounded and sorted), and the type of cross-bedding, point to a desert origin for these sands. Palaeowind directions have been measured from the sands (by measuring the inclination of the layers which are oriented downwind—see Figure 43) and these measurements indicate that the wind blew from the ENE—which is similar to the NE trades blowing across the Sahara today. It seems that 270 Ma ago Britain was in an area flanking an equatorial region. Other palaeoclimatic indicators suggest a northward drift in time until Britain reached its present-day latitude. So the palaeoclimatic evidence shown in the programme strongly suggests that latitudinal drift has occurred through time, but it does not prove continental separation, and neither does it indicate which Pole the area was near when covered by ice some 700 Ma ago.

4.11.2 PALAEONTOLOGICAL AND STRUCTURAL EVIDENCE FOR CONTINENTAL DRIFT

The next section of the programme shows how differences in fossils that are about 500 Ma old, found in north-west Scotland and in Wales, can be explained by the presence of an early 'proto-Atlantic Ocean', and hence an earlier period of continental drift. Similarities between the fossils in Wales and those in southern Newfoundland at this time, and between those in north-west Scotland and those in northern Newfoundland may be explained in the same way. Such palaeontological arguments are comparable with those used by Wegener for the South Atlantic Ocean. In addition

PLATE TECTONIC THEORY
CONSTRUCTIVE PLATE MARGIN
DESTRUCTIVE PLATE MARGIN
CONSERVATIVE PLATE MARGIN

to resolving a paradox in the distribution of fossils, fitting together the continents that border the present-day North Atlantic would amalgamate pieces of a mountain chain some 500–600 Ma old into one continuous belt.

4.11.3 THE GEOMETRY OF THE MID-ATLANTIC RIDGE AND ITS ASSOCIATED FRACTURE ZONES

In this part of the programme, the Mid-Atlantic Ridge is traced southwards from the Reykjanes Ridge. At first sight, the ridge looks as though it follows the shape of the flanking continental shelves, but closer examination shows that it consists of a series of straight sections offset by fracture zones. These offsets can easily be seen on the World Ocean Floor map. The direction in which each fracture zone offsets the ocean ridge suggests movement along a tear fault that is stepped to the east on the south side of each fracture. But Tuzo Wilson suggested in the mid 1960s that sea-floor spreading implied movements in the reverse direction. Subsequently, earthquake studies confirmed the existence of this new class of fault, the transform fault, which is the only part of the oceanic fracture zones along which movement occurs. The original displacement of the ridge was initiated when the adjacent continents first separated, and can still be seen in places as offsets of the continental margin (for example, the continuation of the Romanche Fracture Zone into the African coast).

SUMMARY OF SECTION 4

1 Since World War II, a large amount of data has been collected about the Earth's crust, particularly the oceanic crust, and much of these data had a bearing upon the debate about continental drift.

2 Acceptance of the palaeomagnetic data, which suggested apparent polar wandering, led to the conclusion that movements of the land masses must have occurred, thus establishing the concept of continental drift.

3 Better ocean-depth data and computer-fitting methods provided more convincing fits between continental outlines, particularly across the Atlantic, and better field data helped to confirm the continental reconstructions.

4 The discovery of negative gravity anomalies over deep ocean trenches revealed that the area is not in isostatic equilibrium, and implied that the lithosphere is somehow being dragged down at the trenches.

5 Downward motion at ocean trenches is confirmed by the existence of the inclined seismic zones known as Wadati–Benioff zones.

6 Ocean floor heat-flow measurements showed that there is high heat-flow at ocean ridges, and low heat-flow at ocean trenches.

7 The discovery of magnetic anomaly patterns, which are symmetrical on either side of ocean ridges, led to the Vine–Matthews sea-floor spreading model for the development of the ocean basins.

8 An extensive deep-sea drilling programme, which began in 1968, has sampled all areas of the oceans. Identification and dating of the rocks have confirmed the proposed mechanism of sea-floor spreading, and have produced much additional detail about the kinds of rocks that are involved in the process.

9 If large parts of the Earth's lithosphere (called plates) are moving relative to each other, then it can be shown from geometrical analysis that the relative movement between any two parts can be described as rotation about a common pole. The existence of transform faults, at right angles to ocean ridges and centred on the common pole of rotation, confirms that large areas of the crust are indeed in motion relative to each other.

SAQ 12 Complete the blanks in the following description of plate tectonics:

Ocean floor is envisaged as continuously accreting to a..........(a) plate which is..........(b) inactive, and which interacts with other plates along active zones of..........(c) and seismicity. The movement of the plates over the surface of a..........(d) can be described with reference to a..........(e) of rotation. ....(f) faults trend along the direction of ....(g) circles about the..........(e) of rotation, whereas oceanic ridges between these faults trend along..........(h) circles passing through the ....(e).

SAQ 13 Consider the list of topics we have considered so far in these Units:

A Deep-sea drilling results
B Palaeoclimatic data
C Palaeomagnetic data
D Ocean-floor magnetic anomalies
E Fit of the relief of continental margins
F Seismic studies of directions of crustal movements
G Magnetic polarity reversal timetable

Match these topics with those of the following concepts to which they contributed in a major way:

1 Continental drift (choose *three* items)
2 Sea-floor spreading (choose *three* items)
3 Transform faults (choose *three* items)
4 Plate tectonics (choose *one* item only)

5 PLATE TECTONICS: A SYNTHESIS

Many of the features discussed in Section 3, and a few of those outlined in Section 4, were known to geologists working 40 years ago; but they were not able to explain them all in terms of a single model of the working of the Earth's outer skin. As we saw in Section 4, it was only when the nature of the ocean floors and underlying crust became better known that a truly global model emerged, which could account for a very wide range of observations. This is called the **plate tectonic theory** (or 'model' or 'hypothesis'). As you now know, according to this theory the outer 100 km or so of the Earth consists of slabs, known as lithospheric plates, which are in motion relative to each other and to the interior of the Earth. This global theory is so elegantly simple that it is easy to recall, but it is often easy to forget the *evidence* that supports the theory. We hope that the approach we have adopted in these Units will help you to have a thorough grasp of the evidence that supports plate tectonics.

Recall from Section 4.10 that Morgan identified three kinds of plate boundary. These are called constructive, destructive and conservative margins:

1 **Constructive plate margins,** which Morgan called 'rises' but which we have talked about as 'ocean ridges' (see Section 5.1).

2 **Destructive plate margins,** which are those associated with ocean trenches and related geological activity (see Section 5.2).

3 **Conservative plate margins,** which Morgan described as 'fault type' boundaries at which crust is neither created nor destroyed; we called these 'transform faults' in Sections 4.9 and 4.10 (see also Section 5.3).

A generalized picture of these margins is given in Figure 44. Figure 45 adds some realism to this concept, depicting Africa and South America and parts of two plates.

PASSIVE CONTINENTAL MARGIN

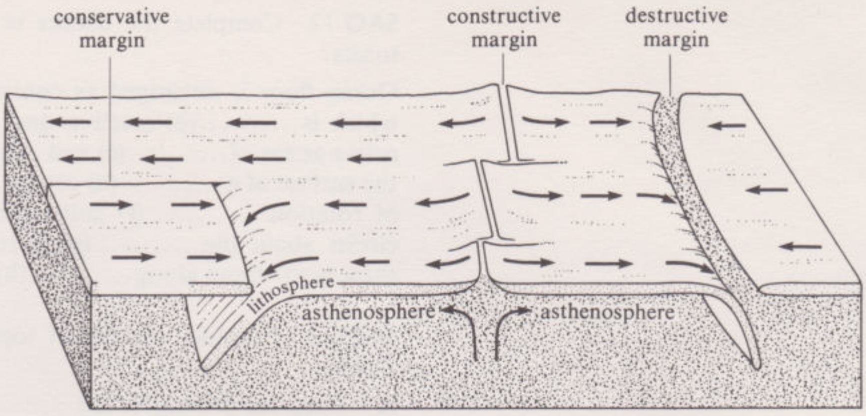


FIGURE 44 Diagram showing the basic concept of plate tectonics. Plates of rigid lithosphere (which includes the crust and uppermost mantle) about 100 km thick overlie the asthenosphere, which is relatively ductile over long periods of time. Mantle material rises beneath *constructive margins* (ocean ridges), and plate material plunges back into the mantle at *destructive margins*. Along a third type of margin, crustal plates slide past each other, forming *conservative margins*.

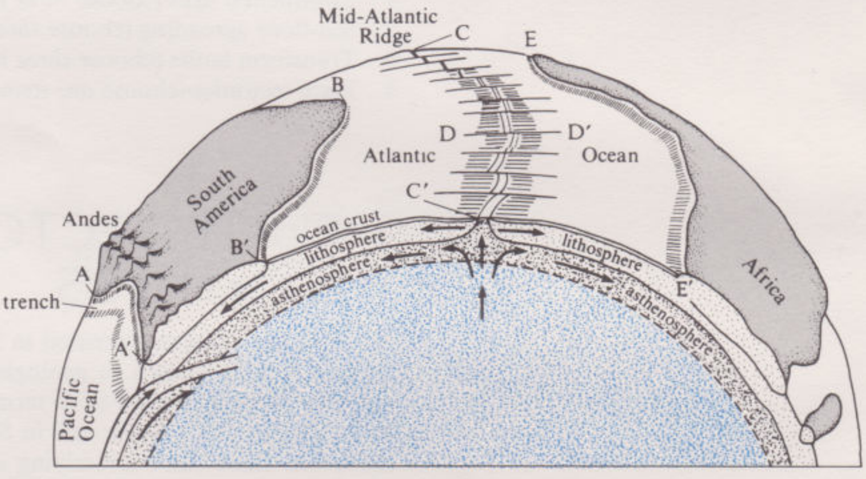


FIGURE 45 Diagram showing the relationships between three crustal plates: the African, the South American, and the Nazca (beneath the east Pacific Ocean). *Note:* The thicknesses of the layers are not to scale.

□ In Figure 45, which of the boundaries marked A–A′, B–B′, C–C′, D–D′, E–E′ is

(a) a constructive plate margin?
(b) a destructive plate margin?
(c) a conservative plate margin?

■ C–C′ is a constructive margin, and A–A′ is a destructive margin. B–B′ and E–E′ are neither, since each is in the middle of a plate. In fact both of these are what is termed a **passive continental margin**. This is simply a boundary between continental and oceanic crust where subduction does not take place (see Figure 49(f)). The part of D–D′ between the ends of the ridge crests is a conservative margin. The rest of D–D′ could be regarded as extinct parts of a conservative margin, since these parts of the transform fault are no longer active.

The differences between these three types of boundary are very important, since each type displays a different kind of geological activity. If we know the characteristics of each, we can use this knowledge to look at older rocks, formed long before the present pattern of plate boundaries came into existence, and work out the original position of these older rocks in relation to former plate boundaries. This helps us to interpret the environment of

formation of many kinds of rock. By placing our observations in the context of plate tectonic theory, many apparently unconnected areas of the Earth sciences have been shown to be related.

In Section 4, we made no concerted attempt to relate the work you did when studying Figures 7–11 to plate tectonics. You should be able to remedy this omission now by completing ITQs 10 and 11. To answer these questions, you will need to study Figures 7–11 and the World Ocean Floor map once more.

ITQ 10 Figure 46 shows the boundaries between the major plates, but does not distinguish whether they are destructive, constructive or conservative plate margins.

Identify whether these plate margins are destructive, constructive or conservative by drawing in the symbols given in the key to the map.

ITQ 11 Complete Table 4 to describe the main features of constructive, destructive and conservative margins. For destructive margins, distinguish between such boundaries involving adjacent oceanic plates (e.g. island arcs in the Western Pacific), adjacent oceanic and continental plates (e.g. the Andean region) and adjacent continental plates (e.g. the Himalayas). In addition, the Table has space for the features of mid-plate regions to be summarized.

Once you have answered ITQs 10 and 11 (and checked your answers), you will be well briefed to read the remainder of these Units, which outlines the geological processes and resultant rock types and structures that occur at each type of plate margin. At this stage in the Course we can give only an outline description, for we have yet to discuss in detail any of the processes that contribute to the formation of igneous, sedimentary and metamorphic rocks. These will be treated in Unit 27 and related to the plate tectonic model.

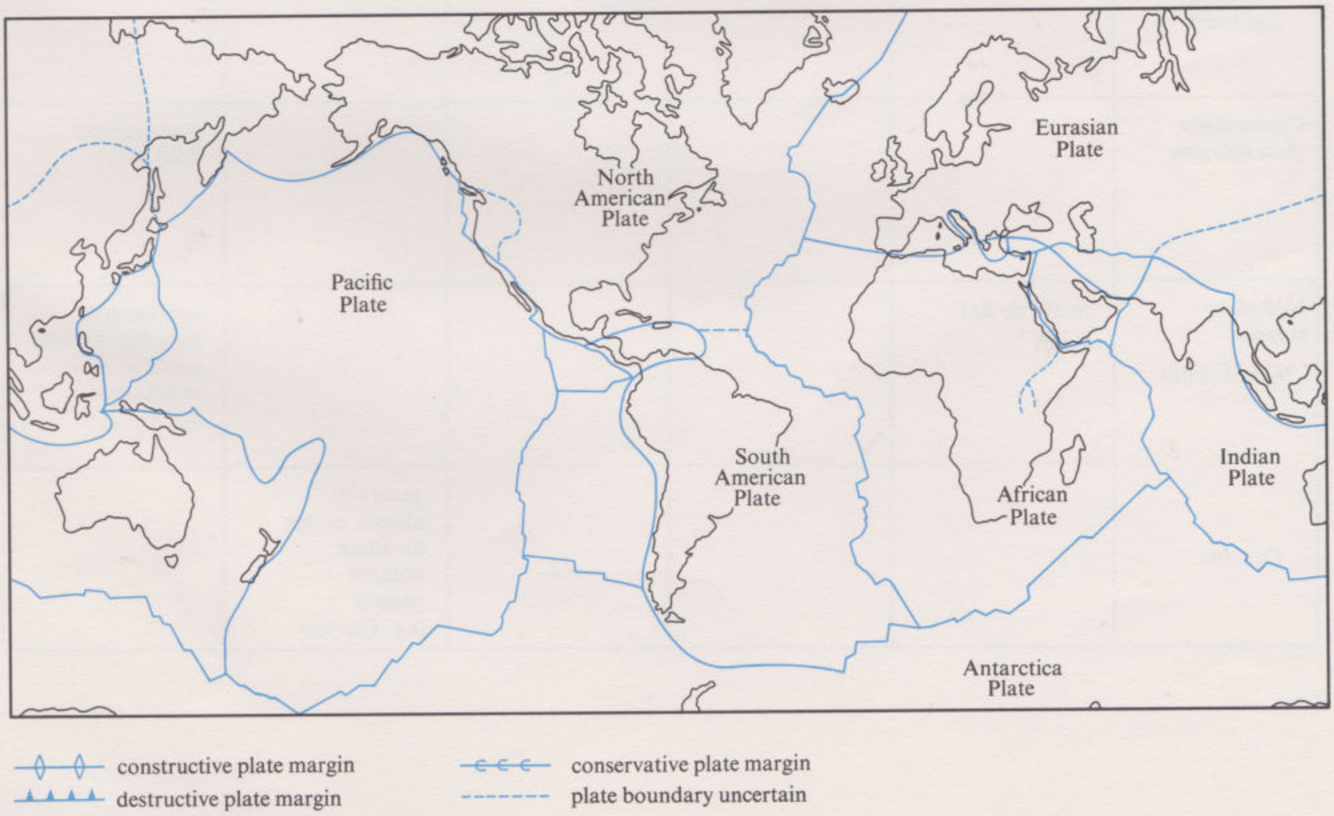


FIGURE 46 Map showing the location of the boundaries between the major crustal plates. For use with ITQ 10.

Figure 42 (p. 55) is a map showing the major lithospheric plates of the Earth and the nature of the seismic activity at their boundaries. This map is rather deceptive, as it does not show the relationships between the plates in polar regions. However, it is much easier to see the way the plates interact with each other on a globe, as shown in the TV programme 'Drifting continents'.

TABLE 4 For use with ITQ 11.

		Relief (name the features present)	Age of rocks (0–10 Ma, 10–100 Ma, or > 1 000 Ma)	Seismic activity (shallow-, intermediate- or deep-focus)	Volcanic activity (effusive or explosive)	Other notable features, such as heat flow (high, average, low) or gravity anomalies
Constructive plate margins			0–10 Ma			
Destructive plate margins	Ocean/ocean		mostly10–100 Ma			
	Ocean continent					low heat flow in trench; negative gravity anomaly over trench
	Continent/ continent		very variable	shallow and intermediate focus		
Conservative plate margins						average heat flow
Mid-plate regions	Continental	relatively flat cratons				average heat flow; no marked gravity anomalies
	Oceanic				generally absent, except for some oceanic islands (e.g. Hawaii)	

DYKE

5.1 CONSTRUCTIVE PLATE MARGINS

The purpose of this Section is to relate some of the rock specimens you have in your Experiment Kit (S3 basalt; S4 peridotite; S5 gabbro) to the processes thought to operate at constructive plate margins. Given that such processes are responsible for the formation of some 70% of the Earth's surface area, they deserve our attention. The second TV programme, 'Volcanic Iceland', is entirely devoted to the key features of a constructive margin, and it shows many such features found in Iceland. The programme should be watched *after* you have had at least a first read through this Section. Notes on this programme are in Section 5.1.1.

As already shown in Figure 28, oceanic crust has a remarkably simple layered structure. How is this crust generated in such a uniform way?

Figure 47 summarizes the main features of constructive plate boundaries. It must be stressed that this is a hypothetical model, based both on investigations of ocean ridges and on studies of slices of presumed oceanic crust that have been thrust up into continental regions. At the time of writing, deep-sea drilling has penetrated oceanic crust only to a depth of 600 m.

Figure 47a shows mantle material rising under the ocean ridge, 'filling the gap' as the two plates move away from each other, and by so doing, actually causing the crust to grow. But what is the *process* by which the plates grow? And how is the characteristic layered structure (shown in Figure 28 and the left-hand side of Figure 47b) of oceanic crust produced? Before speculating on the processes that might be operating beneath ocean ridges, a little more must be said about the nature of the layers.

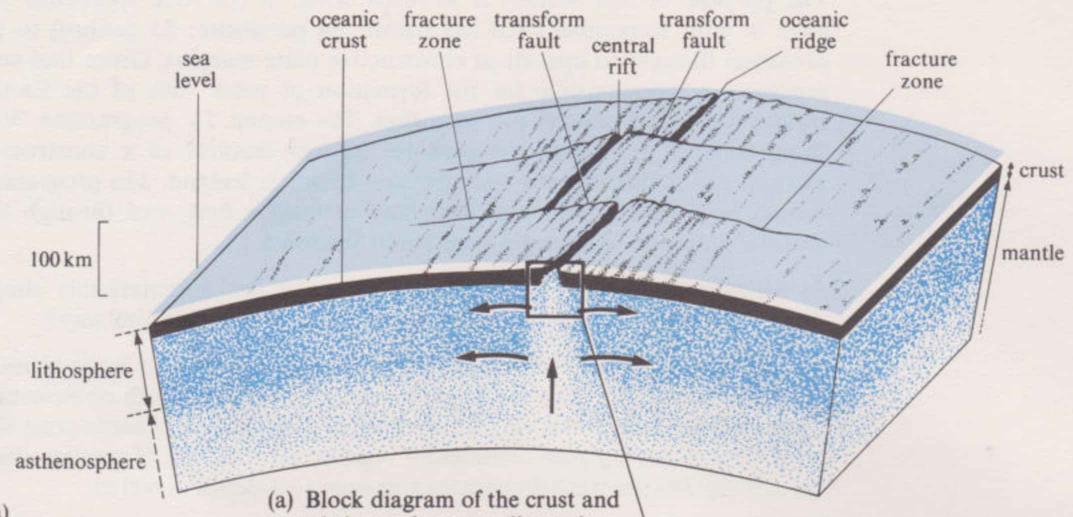
Deep-sea drilling to date has penetrated into layer 2. Layer 1 consists of sedimentary rocks, formed either from the dead remains of organisms living in the surface waters of the ocean, or from chemical precipitates on the sea bottom, such as manganese nodules (Figure 47c). Layer 1 may also contain volcanic ash that has settled out through the ocean water, but is remarkable for its lack of sedimentary particles derived from continental crust.

□ Why do you think layer 1 thins and becomes absent towards the ridge crest shown in Figure 47b?

■ Sediment starts to accumulate only after oceanic crust has formed (that is, in layer 2 and below). As the crust is youngest over the ridge crest, and oldest on the flanks (on the edges of the diagram), sediment has obviously accumulated for a longer period over crust that has now moved away from the spreading centre. This thickening of layer 1 away from ridge crests is well documented by numerous seismic surveys and by the Deep-Sea Drilling Project.

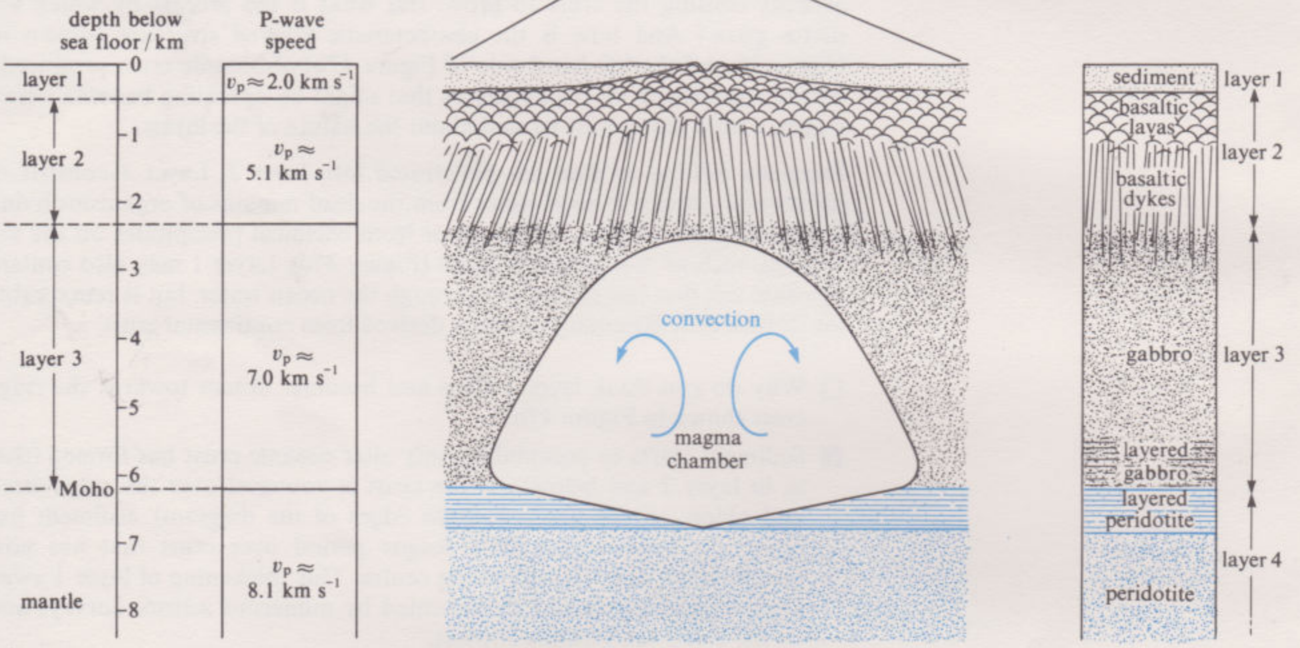
Layer 2 has a fairly uniform thickness of just under 2 km, and is exposed in the vicinity of ocean ridges. Here, its surface is seen to consist of basalt pillow lavas (the pillow shape is characteristic of lavas formed underwater; see Figure 47d). The lower part of layer 2 is known from deep-sea drilling to be formed of vertical sheets of igneous rock known as **dykes** (Figure 47e). The structure of this layer is analogous to a pack of playing cards standing vertically, each card representing a single dyke. The dykes result from basaltic magma rising into vertical cracks in the crust and then solidifying. These cracks exist because the crust is being extended. The boundary between the dykes and the pillow lavas is not abrupt, for some dykes penetrate the lavas. Layer 3 incorporates sheeted dykes that extend down into gabbro, a rock with the same chemical and mineral composition as basalt, but with a larger crystal size (the gabbro is specimen S5 in your collection).

FIGURE 47 The features and processes characteristic of constructive plate boundaries (see the text for full discussion).



(a)

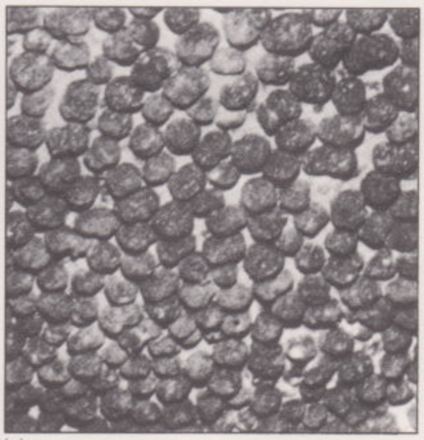
(a) Block diagram of the crust and mantle beneath a spreading axis (oceanic ridge).



(b)

(b) Enlargement of part of (a), showing an interpretation of the crustal and mantle processes that operate during sea-floor spreading, and the nature of the layers produced by these processes. The size and shape of the magma chamber beneath an oceanic ridge remains the subject of debate.

(c)



(c)

(c) *Layer 1*: deep-sea sediments. Left: a calcareous ooze produced by microscopic organisms that live in ocean surface waters and that fall to the bottom after their death (average diameter a few thousandths of a millimetre). Right: manganese nodules (average diameter 6 cm).

FIGURE 47 continued. (d) to (f) are examples taken from exposures of rocks believed to be oceanic crust that has been thrust up into continental crust (these examples are from Cyprus).

(d) *Layer 2*: basaltic (see specimen S3) pillow lavas extruded onto the ocean floor along oceanic ridges.

(d)

(e) *Lower part of Layer 2*: vertical sheets of basaltic rock (known as dykes).

(e)

(f) *Lower part of layer 3*: coarse-grained igneous rock with the same chemical and mineral composition as basalt (it is known as a gabbro; specimen S5), showing a layered structure.

(f)

□ If the chemical and mineral compositions of basalt and gabbro are the same, what is the reason for their different crystal sizes (recall the AV sequence, 'Igneous rock formation', associated with Units 5–6)?

■ The larger crystal size of gabbro is due to the fact that it cooled more slowly than basalt. In the crustal environment we are discussing, this is hardly surprising, since the gabbros must have formed several kilometres below the basaltic lavas.

It is possible that the upper part of the gabbros of layer 3 are uniform in structure, in contrast to the lower part, which is layered (see Figure 47f; we shall return to the significance of this later).

OPHIOLITE SEQUENCE

OBDUCTION

The base of layer 3 is of course marked by a seismic discontinuity—the Moho (see Section 4.8). Layer 4 is generally agreed to be composed of *peridotite* (specimen S4), which has a greater density than gabbro or basalt. The top kilometre or so of layer 4 is thought to be composed of *layered peridotite*.

You should note that the boundaries of the four layers are determined from seismic evidence, and that seismic waves cannot distinguish basalt pillow lavas from basalt dykes. The boundary between layers 2 and 3 lies within the sheeted dykes and is thought to result from the recrystallization of dykes at deeper levels due to heat from below.

The kind of rock sequence described above is known as an **ophiolite sequence** and can be seen in continental regions in many parts of the world. All these ophiolite sequences occur in regions interpreted as ancient destructive plate margins in which slices of oceanic crust, instead of being subducted *down* into the mantle, have been thrust *upwards* onto continental crust. This process is known as **obduction**. Small examples of the association between basaltic lavas, dykes, gabbros and peridotites can be found in Britain (for example, in the Lizard Peninsula in Cornwall, in the Lleyn Peninsula and Anglesey in North Wales, and in Southern Scotland). What kind of igneous process could form the rock sequence just described? Any hypothesis must account not only for this sequence, but also for the uniform thickness of layer 3 and, of course, for sea-floor spreading itself!

Figure 47b shows a large chamber filled with magma of basaltic composition. The existence of this body of liquid is postulated both because P-wave speeds beneath ocean ridges are lower than in normal mantle, and because it could produce the layered structure we have been examining.

□ What would happen to any crystals that solidified from the liquid, bearing in mind that experimental results suggest that the first crystals to appear have a greater density than the liquid that surrounds them?

■ Such crystals would sink to the bottom of the chamber.

It is thought that these crystals sinking to the bottom of the magma chamber account for the densest layer of peridotite accumulating there. Layering in both the peridotite and the gabbros is produced by convection currents within the chamber, which at times may prevent all but the densest crystals settling. During periods when there is no convection, crystals of all densities will settle (densest fastest), and so layers of different density are produced. The uniform gabbro is produced by steady crystallization on the walls of the chamber, so that away from the region beneath the ridge crest the magma is totally solidified. Above the chamber, magma is constantly being forced upwards to form dykes, which in turn 'feed' the outpourings of lava on the ocean floor. The dykes continually intrude between their predecessors, much as an extra playing card might be forced up into the vertical stack of cards we imagined earlier. Whether this is the driving force behind sea-floor spreading, or whether the dykes are filling spaces left as the ocean ridge is pulled apart we shall see in Section 5.4.

Finally, why are the ocean ridges raised above the abyssal plains, and why are these regions so rugged? The answer to both questions relates to the fact that the region is one of high heat flow. Because this part of the crust is hotter, it is less dense, and so it stands higher than the surrounding regions. As the newly-formed crustal material moves away from the spreading centre, it cools, and so its density increases and its elevation decreases. The drop in height is accommodated along faults running parallel to the ocean ridge, which accounts for the characteristic 'grain' of the relief depicted on the World Ocean Floor map.

5.1.1 VOLCANIC ICELAND (TV PROGRAMME)

This programme, filmed almost entirely in Iceland, illustrates many of the characteristic features of ocean ridge volcanism. Of course, Iceland's very existence on land means that it is an anomalous piece of ocean ridge. It is

believed that the particularly intense and continuing volcanism that has developed here owes its origin to the combination of a hot column of magma rising from the deep mantle of the Earth, and the normal processes of volcanism that produce the ocean ridge. Nevertheless, many of the volcanic features resemble those of the zones of normal ocean ridge that have now been investigated using submersible craft. Iceland provides a unique opportunity for us to study a more accessible piece of constructive plate margin on land.

We start by looking at a version of the World Ocean Floor map on which earthquake epicentres have been marked with pink spots. Those along the Mid-Atlantic Ridge record the sites of earthquakes—both those associated with submarine volcanic eruptions along the ridge, and those along transform faults *between* adjacent zones of ridge that have been offset laterally. Attention is focused on the zone just south of the Azores, which has been studied in detail. Here the ridge takes the typical form of a large rift valley with subdued hills, each of which is an active, or recently active, volcano. An animation is used to show how tensional stresses through the depth of the ocean lithosphere build up at right angles to the ridge. These stresses form vertical fissures through which sheet-like bodies of magma rise from chambers below to produce dykes. Typically, eruptions start with earthquakes and rifting. After this, several volcanoes along the rift build up as magma, which rises through dykes, reaches the surface and is erupted. Initially, each volcano may be active for months or even years before activity wanes. After a respite, perhaps lasting ten years, further periods of activity may occur at each site. Hundreds of years later, a new fissure will form on the flanks of the old volcanoes, and subsequent activity will produce a new series of volcanic structures, each with its own dyke complex beneath. The animation speeds up the geological processes, which would last about 30 000 years. As each new volcano forms, the older ones are pushed across towards the edge of the rift. So, activity on ocean ridges is produced essentially by forces that allow a rift zone to form, and new volcanoes are continuously being produced along the axis of the rift zone. Older volcanic features 'spread' away towards the flanks, becoming part of the older ocean lithosphere.

Further north, the ocean ridge bifurcates through Iceland (Figure 48). A line of earthquake epicentres along the Reykjanes ridge to the south extends on land to form a western volcanic arm. The eastern arm connects some of the main centres of activity in recent decades: Surtsey and the other Vestman Islands in the south, Askja in central Iceland and Krafla in north Iceland. North of Iceland there is again a single active zone—the Koblenskey ridge. The whole island is about 16 million years old (compare this with the oldest parts of the North Atlantic, which are about 150 million

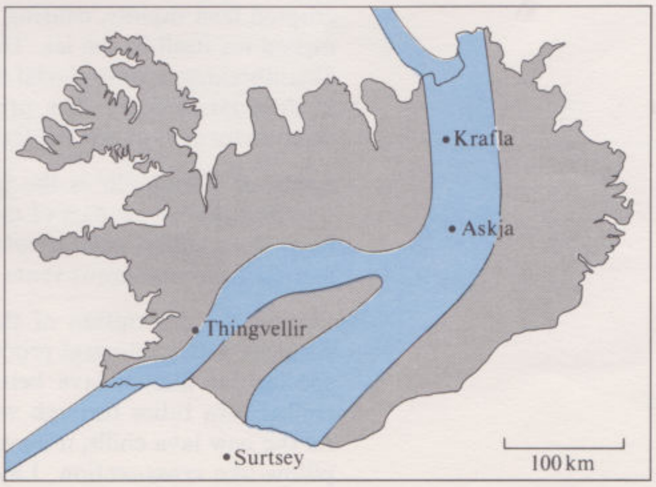


FIGURE 48 Map of principal localities visited in the TV programme 'Volcanic Iceland'. The active areas of the ridge are shown in blue.

CALDERA

SHIELD VOLCANO

years old), and it has hundreds of volcanoes, most of which are extinct and are located to either side of the active zones indicated in Figure 48. There are some 20 large *active* volcanoes and volcanic systems today, a few of which are located beneath the huge ice sheets that cover about 10% of the island. Typically, about every 100 years the activity at a large Icelandic volcano gives rise to major basalt lava flows and eruptions of black cinder-like material. Eruptions may continue for several years before the volcano enters a period of repose, which is often typified by the discharge of steam, hot water and mud from surface pools. All these phenomena provide evidence that hot, molten magma is never more than a few kilometres below the surface.

We first examine some of these features at the Krafla caldera, where some of the most recent eruptions of Icelandic lava took place between 1975 and 1984. A **caldera** is a more-or-less circular collapse structure often found above the main vent of a volcano. It forms when the magma chamber beneath the volcano is emptied and not refilled from below. The rocks above the chamber collapse along circular fractures, or faults—which form the perimeter of the caldera—into the void left by expulsion of the magma. The zone of lava eruption through the Krafla caldera is marked by a line of small cones. These cones built up as molten magma erupted vigorously into the air in the form of fire fountains and then fell back around the base. The line of cones is an expression of a small-scale rift, or fissure, that lies on the spreading axis of the ridge. It is centred on the Krafla caldera, where most of the eruptions take place, but can be traced for about 80 km along the ridge. The fissure is underlain by a dyke system, which reaches its maximum activity beneath the Krafla caldera where there is a large cylindrical magma chamber. When magma rises to the surface of the fissure it moves out sideways, like an enormous river, to form extensive lava flows that travel many kilometres but are only one or two metres thick. The programme illustrates the way in which new lavas cover older, more weathered lavas. The time gap between them reminds us that rather than being a continuous, conveyor-belt process, sea-floor spreading is a jerky, or spasmodic, process when viewed on a human time-scale.

Next we travel to Thingvellir, in south-west Iceland, where there is a particularly fine example of a five-kilometre-wide rift valley. Here a dyke system connecting two volcanoes at the north and south ends of the rift has cooled and contracted, allowing the region between to collapse along almost vertical, faulted walls. In the centre of the rift, some open fissures, which are ten metres wide and 20–30 metres deep, provide good evidence that the crust is under tension—even though there has been no volcanism at Thingvellir for 2 000 years. To the north is the dome-shaped **shield volcano**, Skjaldbreidur, formed by the rapid build-up of overlapping lava flows from a single eruptive vent. This contrasts sharply with the *table mountain* shape of Hrafnaborg to the east. Table mountain volcanoes are uncommon on ocean crust; in Iceland, they result from eruptions beneath the thick ice-sheets that covered the whole island 10 000–70 000 years ago. The ice chilled the erupted lava rapidly, causing the volcano to be confined to the hole that it melted for itself in the ice. The ice melted away about 10 000 years ago, so Skjaldbreidur, a post-glacial volcano, must have formed much more recently than Hrafnaborg. The processes of shield-volcano and table-mountain volcano formation are illustrated using animations in the programme.

South of Thingvellir is the largest lake in Iceland, Thingvallavatn, which occupies the lowest part of the rift valley. The land rises beyond the lake to form the complex *central volcano*, Hengill, which has had a long history of activity from numerous vents.

During the description of these volcano types, we digress to draw some parallels with geological processes elsewhere on the ocean ridge. We show a spectacular film of lava being erupted underwater near Hawaii, forming chilled lava tubes through which molten lava is squeezed like toothpaste. As the new lava chills, it leaves another tube behind while the front forms a pillow-like cross-section. Layers of pillow lavas are typical of submarine eruptions, but they are also found in Iceland where lava erupted gently into

sub-glacial lakes formed from melt-water. Consequently, pillow lavas often occur as the foundations of table mountains. If lava is erupted more rapidly into water, then it explodes and often breaks into small glassy fragments. These may collect to produce layers of brown or black sedimentary-like material higher in a table mountain sequence. These rocks are known as *hyaloclastites* (from the Greek: *hyalos*, glassy; *klastos*, fragmental). So sequences of sub-glacial pillow lavas and hyaloclastites are typical of Icelandic table-mountain volcanoes.

The next Icelandic locality illustrated is one of the best preserved and largest calderas—part of the central volcano, Askja. The ten-kilometre-wide outer caldera is some 4 000–5 000 years old but, in the south of this main caldera, is a second, smaller and younger caldera, which formed in 1875 and which is now filled by the caldera lake Oskjuvatn. The 1875 eruption was a large, explosive event, which produced a pale brown pumice-like rock that covered a vast area over eastern Iceland. Some even fell as a fine dust in Scandinavia. At the same time, some magma drained out to the north of Askja forming lava flows on a fissure 50 kilometres away. This shows that, like Krafla and many other large Icelandic volcanoes, Askja has its own interconnected dyke–fissure system. The same is probably true of most volcanoes on ocean ridges.

In the Askja area, various Icelandic and Open University geophysicists are studying ways of predicting eruptions, by watching for changes in ground levels and for tilting, both of which occur as magma begins to force its way up from deep beneath the ground. Gravity can also help us detect the presence of the magma. Magma is less dense than solid rock, and therefore generates, progressively, a negative gravity anomaly as it rises to shallow levels (all other things being equal).

The last locality we visit is in the south of Iceland, and it has provided perhaps one of the most spectacular sites of volcanism in recent times. The Vestman Islands are also on the eastern arm of the spreading ridge, and their number was increased in 1963 by the eruption of a completely new island, since named Surtsey (Figure 48). In 1973, there was a large eruption on the island of Heimaey, which almost overwhelmed this major fishing town. The lava was stopped, however, by the rather original trick of pumping large volumes of seawater on to the flows, which solidified, and thus failed to block the harbour. The town has benefited ever since by using the residual heat in the lava flows, which is extracted through a water circulation system, for central heating of houses.

The programme closes with views of Krafla geothermal power station, which generates about 30 megawatts of power, enough for around 30 000 homes.

5.2 DESTRUCTIVE PLATE MARGINS

A destructive plate margin is a boundary between two lithospheric plates at which oceanic crust is destroyed by subduction into the mantle. There are two types of destructive margin: ocean/continent and ocean/ocean. Figure 49 shows the main features of margins of these types. The great variety of complex igneous, sedimentary and metamorphic processes that occur on these margins will be discussed in more detail in Unit 27.

Ocean/continent and ocean/ocean destructive margins have a number of features in common (Figures 49b, 49c and 49d):

1 subduction of oceanic crustal material is revealed by an inclined zone of earthquakes (Wadati–Benioff zones), which are generally steeper beneath ocean/ocean margins;

2 explosive volcanic activity;

3 ocean trenches;

4 negative gravity anomalies over the trenches, positive gravity anomalies over island arcs or mountain ranges.

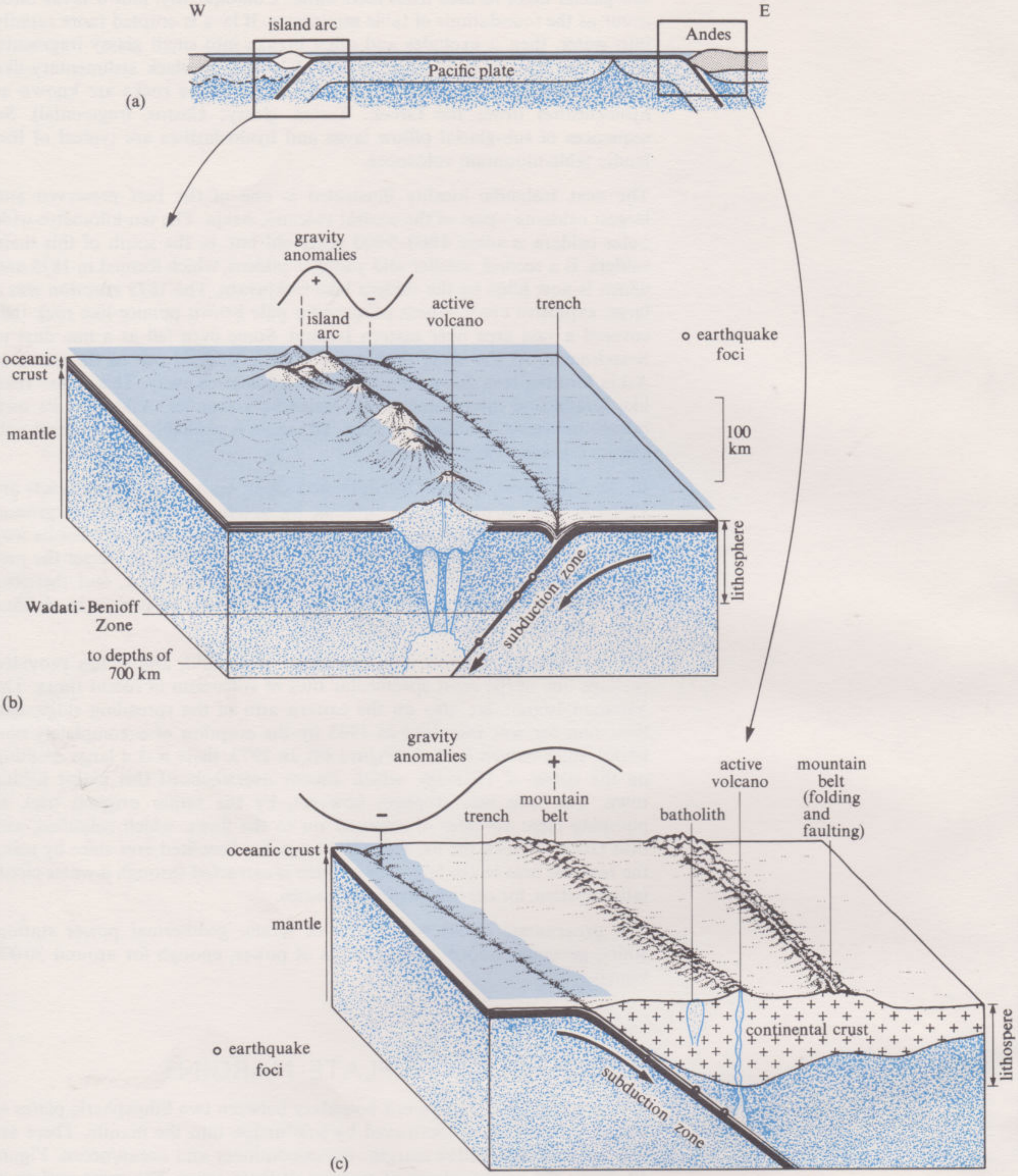


FIGURE 49 The features of the two types of destructive plate margin.

(a) East-west sketch section across the Pacific Ocean, showing the location of ocean/ocean (island-arc type) and ocean/continent (Andean-type) destructive plate margins.

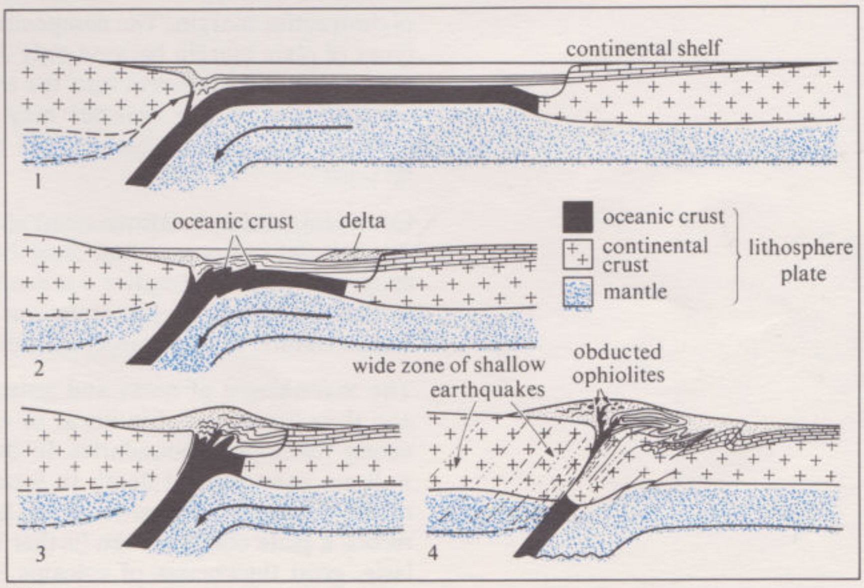
(b) Block diagram showing the main features of an ocean/ocean (island-arc) destructive margin.

(c) Block diagram showing the main features of an ocean/continent (Andean) destructive margin.

FIGURE 49 continued

(d) Typical Andean volcanic cone, consisting of a mixture of lava and volcanic ash, with the latter being the predominant component.

(e) Folded metamorphic rocks typical of the deeper parts of destructive margins, and indicating compression of the crust.



(f) Sequence of events leading to the formation of a continent/continent (Himalayan) plate margin. 1 and 2: the early stages, in which a passive *continental* margin is converging on an ocean/continent destructive *plate* margin. 3 and 4: the continents meet and a continent/continent plate margin is formed.

Note how slices of oceanic crust are caught up in the continental rocks (obducted) and exposed at the surface as ophiolitic complexes. Plate boundaries of this type contain older relics of earlier, ocean/continent destructive margins, including volcanic activity.

ANDESITE

BATHOLITH

□ Why do you think oceanic crust nearly always dives beneath continental crust at destructive plate margins?

■ Because oceanic crust is denser than continental crust.

□ Given that one plate is sliding beneath another at destructive plate margins, what is the source of heat that generates the magma that feeds the volcanic activity in these regions?

■ Friction between the two plates generates heat. Melting also occurs as the down-going plate descends into hotter regions. The resultant igneous activity is largely responsible for building up the island arcs on previously existing oceanic crust (Figure 49b).

□ Would you expect the types of volcanic rock in ocean/ocean destructive margins to be the same as, or different from, those in ocean/continent destructive margins? Look carefully at Figures 49b and 49c, and bear in mind that in 49b, rocks of basaltic–gabbroic composition dominate each plate, whereas in 49c rocks of both basaltic–gabbroic and rhyolitic–granitic composition are involved.

■ Not surprisingly, the island-arc volcanic rocks are predominantly basaltic but the Andean-type destructive margins are dominated by volcanic lavas intermediate in composition between basalt and rhyolite, and known as **andesites** (named, of course, after the Andes). In fact, taken overall, the composition of the continental crust is andesitic; only its upper part has a granitic composition. In other words, if the rocks that make up the continental crust were mixed up and made homogeneous, the resulting rock would have the composition of andesite. However, andesites are also formed beneath island arcs at the later stages of their evolution, as will be discussed in more detail in Unit 27.

Ocean/continent destructive plate margins are also characterized by the occurrence of large intrusive masses of granite, produced by the partial melting of the plate above the subduction zone. Specimen S1 in your Experiment Kit came from one such intrusive mass. The granitic magma, being less dense than the surrounding rocks, moves upward in the crust, and may reach within a few kilometres of the surface. There it solidifies to form huge elongate masses of granite called **batholiths**, which may later be exposed at the surface if the overlying rock cover is removed by erosion.

Continental rocks may be crumpled and metamorphosed at destructive margins: details of these processes are discussed in Unit 27.

Sediments accumulate in the ocean trenches associated with the two types of destructive margin. The composition of these sediments differs in the two types of plate margin because only Andean-type margins contain fragments of continental rock swept into the trenches. In both margins, the sediments accumulating in the trenches may eventually be carried down the subduction zone, and be 'plastered' on to either the island arc or the continental crust.

Continent/continent (Himalayan) plate margins are hybrid margins because the two slabs of continental crust that eventually collide first evolve either as passive or as destructive continental margins (Figure 49f). For example, in the Himalayan region abundant igneous rocks provide evidence of its former nature, as an ocean/continent plate boundary.

The assemblages of rocks and structures produced at destructive margins, and their arrangement in linear or curved belts provides a means of recognizing 'fossil' plate boundaries. In Britain, the granites of Devon and Cornwall are connected at depth to form a batholith, which has intruded as a result of a plate collision some 300 Ma ago, and those in southern Scotland record a plate collision even further back in time, around 450 Ma ago. Similarly, great thicknesses of volcanic and sedimentary rocks in North Wales and the Lake District suggest that these regions were the sites of island arcs between 500 and 400 Ma ago.

The net effect of the processes at destructive margins is to add both volcanic and intrusive material, of composition intermediate between basalt (gabbro) and rhyolite (granite), to the continents. (You will learn in Unit 27 that basalt has the same *chemical* composition as gabbro, and rhyolite has the same *chemical* composition as granite.) The volcanic rock with this intermediate composition is andesite.

5.3 CONSERVATIVE PLATE MARGINS

A plate margin at which crust is conserved, in other words, neither created nor destroyed, is called a *conservative plate margin* (Figure 50) at which adjoining plates are sliding past each other, producing shallow earthquakes.

The offsets in ocean ridges are transform faults, and though the ocean ridges as a whole are constructive margins, these (relatively) small offsets in the ridges are strictly speaking short pieces of conservative margin. There are other instances however where the boundary between two plates is dominantly, or entirely, of the conservative margin type. You will remember from our discussion of transform faults that they take their name from the way in which the faults terminate. At each end, the faults *transform* into a different type of plate boundary, be it a constructive margin (ocean ridge) or a destructive margin (island arc or Andean-type mountain belt).

□ Can you recall from your study of the World Ocean Floor map a place where an ocean ridge runs into a continental edge, and is *transformed* into a different feature of major dimensions? (*Hint:* Look at the western side of North America, and compare it with Figure 56 in the answer to ITQ 10.)

■ The East Pacific ridge runs into the long thin inlet known as the Gulf of California, south of Los Angeles, and is transformed into the San Andreas fault, which then runs up the coastal strip to San Francisco before striking out to sea again and transforming back into the Gorda Ridge. You may recall that this was mentioned briefly in the AV sequence 'Crustal patterns'.

You will recollect from Units 5–6 (Section 1.5) that the San Andreas Fault system is very active and that in the 1906 San Francisco earthquake, there was lateral movement across the fault of 6.5 m. You can now see why this movement occurred, and why the whole coastal area of California is a very active earthquake zone—in this area, the Pacific plate is moving inexorably north-westwards with respect to the North American plate (Figure 42). This movement is taking place on geological time-scales; locally at present some

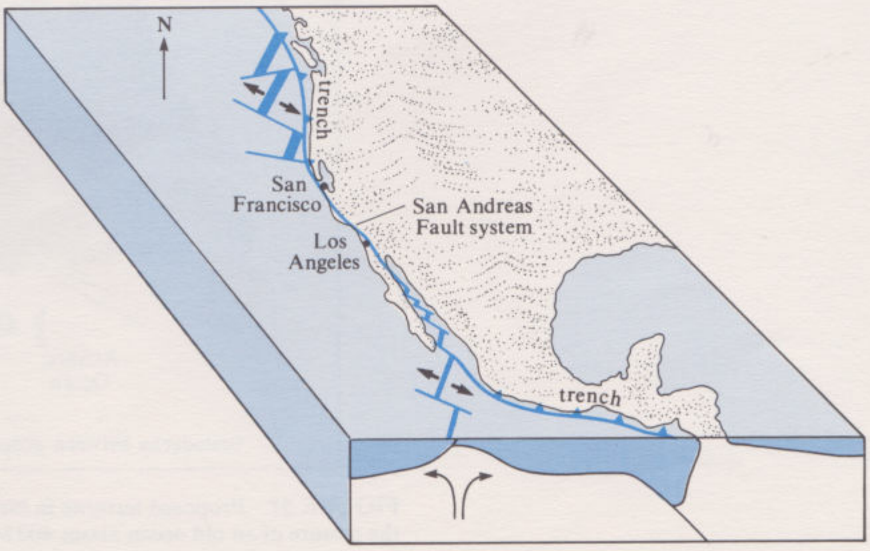


FIGURE 50 The features and processes characteristic of conservative plate margins (see text for full discussion).

TERRANE

parts are moving and some parts are temporarily 'locked'. A network of equipment is monitoring any slight movements and any build-up of strain where there is no movement. You will also realize why further earthquakes are inevitable in California, for the foreseeable future. The only question is whether the earthquakes will be numerous and frequent, and therefore relatively small, or whether the fault will 'lock' until the stress builds up to enormous levels and then be released in an earthquake of immense destructive power.

Clearly, conservative plate margins are of considerable contemporary significance. But in the early 1980s, many geologists gradually came to accept that lateral movement along faults with displacements up to hundreds of kilometres has also been very important in a different way throughout much of the geological past, certainly for several hundred million years.

In Section 5.2, we summarized how volcanic activity at destructive margins adds material to the existing continental crust. We have also discussed how collisions of lithospheric plates have resulted in the joining together of plates to form mountain belts after which the plate margin becomes inactive. More recently, however, it has become clear that many parts of the continental crust have been constructed as the result of the accretion of many much smaller pieces of continental crust, sometimes referred to as micro-plates. These are usually much smaller than the minor plates shown on Figure 42.

A fragment of continental crust of this type is called a **terrane**, and such fragments are recognized as discrete units because they have internally consistent geological features, but do not match in any way the adjoining crustal material. Indeed, a terrane is separated from adjoining crust by a zone that shows evidence of major faulting, or of a zone of major disruption of the rocks called a *mélange* (a French word meaning mixture).

The idea is that at least some of these terranes have been transported along transform faults that have been active as conservative margins for quite long periods of time. The terranes can be transported quite long distances, of the order of hundreds of kilometres, before being 'plastered' onto a totally unrelated piece of continental crust, which may have formed in a different climatic zone under entirely different geological conditions. An example of an area that has been interpreted in terms of this idea is shown in Figure 51.

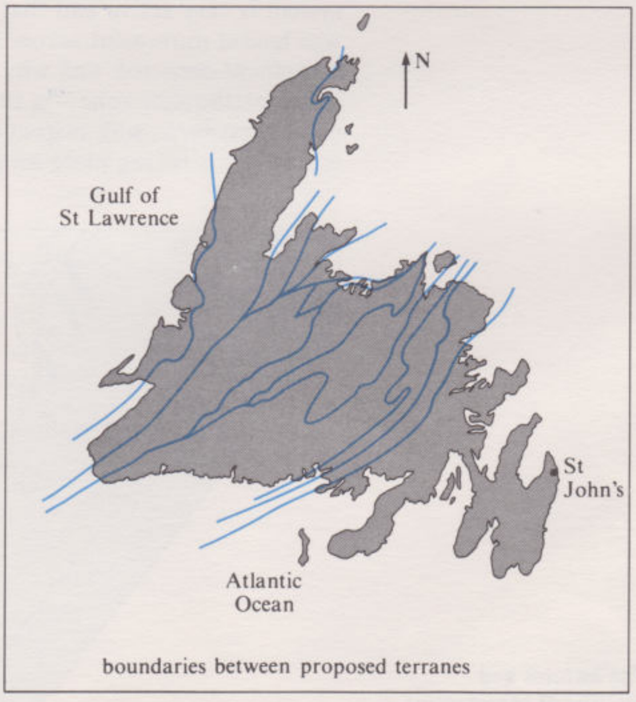


FIGURE 51 Proposed terranes in Newfoundland. These rocks were involved in the closure of an old ocean about 400 Ma ago.

The concept of terranes has enabled geologists to make sense of a number of areas in which previously the geology could only be described as apparently chaotic. This is another illustration of the way in which the theory of plate tectonics has contributed to the synthesis of a wide variety of disparate geological observations into a coherent whole.

SAQ 14 Select from the array below the characters of the three types of plate margin identified on the three blank arrays. Put a tick in the appropriate boxes to indicate your choices.

1 Positive gravity anomaly over depressed region	2 Basaltic volcanic activity	3 Narrow zones of shallow-focus earthquakes	4 Negative gravity anomaly over depressed region
5 Island arcs	6 Large masses of granite (batholiths)	7 Metamorphism	8 Relatively low heat-flow values over depressed areas
9 Andesite volcanic activity	10 Broad seismic zone with earthquake foci lying along an inclined plane	11 Relatively high heat-flow values over elevated region	12 Uniformly layered crustal structure
13 Extensional features	14 Shallow- and intermediate-depth earthquakes in same region	15 Positive gravity anomaly over elevated region	16 Abundant basaltic dykes

Constructive margins

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Destructive margins

ocean/ocean

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

ocean/continent

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

5.4 THE CAUSES OF PLATE MOTION

Up to now, we have described plate movement without attempting to discuss the mechanisms that cause it, apart from mentioning that the proposers of the theory of plate tectonics suggested that mantle convection currents might be involved. It is extremely difficult to investigate such mechanisms because not only are they physically remote—buried deep in the Earth—but also the mechanisms operate on a vast scale and over very long periods of time.

You will remember that in Section 4.4 we explained that the part of the mantle known as the asthenosphere, in which isostatic adjustment takes place, must be displaying ductile behaviour on a long time-scale. The asthenosphere includes the low-speed layer, which is likely to be ductile since it is partially molten. This suggests that the low-speed layer may be the zone across which the plates are sliding over the mantle. However, as we also discussed in Section 4.4, the seismic evidence shows that the low-speed layer is absent in some places, particularly beneath some of the old, relatively cool cratonic parts of the continents. Since even where the layer is absent, the plate above the area where it would have been is still in motion, it follows that this layer is certainly not the only one across which movement of the plates is taking place. The whole of the asthenosphere can deform by ductile flow quite fast enough to allow plate movement, the speed of which is of the same order of magnitude as the rate of restoration of isostatic equilibrium. But regardless of the location of the zone of movement, the question still arises: what is causing this movement?

Various suggestions were made by earlier workers, even before continental drift and the plate tectonic theory became generally accepted (see Section 3.6 for two of these earlier suggestions). These suggestions were all based upon the assumptions that there are convection cells in the mantle below the lithosphere and that ocean ridges, with their high heat-flow, were over a rising limb of the convection cell, and that subduction zones were associated with sinking limbs of convection cells. Two examples are shown in Figure 52a and b. The size of the convection cells has been a topic for discussion and argument ever since the idea was first proposed.

However, the whole question of the nature of mantle convection, and its relationship to plate movement, was given a new complexion by Dan McKenzie, working at Cambridge University, who devised a way of detecting mantle convection cells, and in particular the location of both upwelling parts and down-going parts. McKenzie used elaborate satellite remote-sensing techniques to investigate the convection patterns in the part of the upper mantle that is beneath the oceans.

This is an indirect approach that relies on the fact that density differences within the mantle are reflected in small gravity anomalies at the Earth's surface. Over an upwelling part of a convection cell, the mantle is hotter

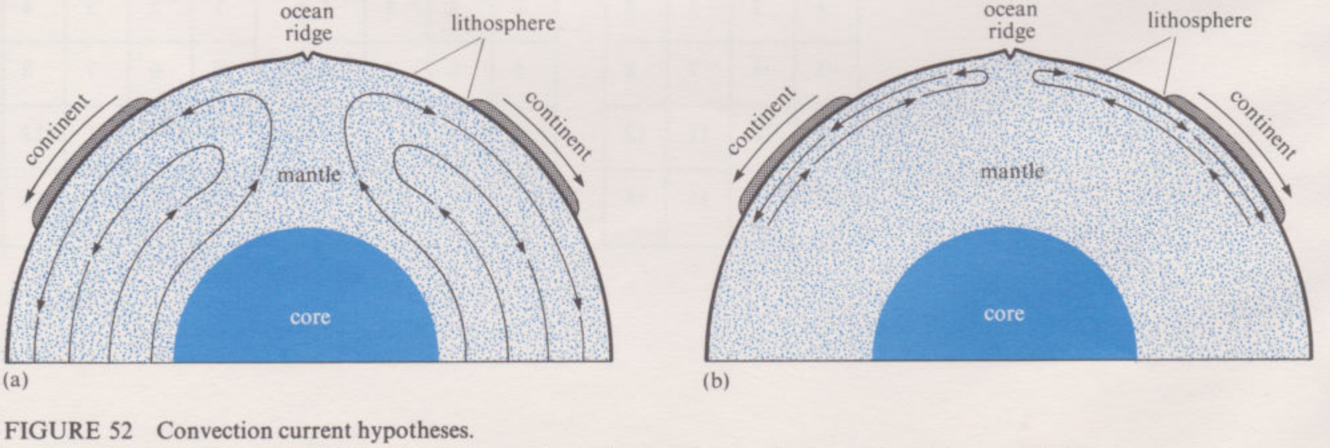


FIGURE 52 Convection current hypotheses.

(a) Convection current hypothesis involving the mantle, and accounting for the sites of ocean ridges and subduction zones.

(b) Modified convection current hypothesis involving long, flat convection cells within the Earth.

and so the material of the mantle is expanded and therefore less dense. We would expect such areas to be characterized by negative gravity anomalies. However, the effect of the upward motion is to cause the sea-floor to bulge slightly, and so there is an extra volume of material present. As it happens, the increase in mass caused by the bulging slightly exceeds the decrease in mass caused by the material being less dense, so there is a net excess of mass, and hence a slight positive gravity anomaly. Conversely, there are negative gravity anomalies over cooler, and therefore denser, downgoing convection limbs because the sea-floor is dragged down slightly there. These anomalies extend over distances of 500 km or more across the ocean.

These variations in g affect the height of the sea surface. Where there is a positive gravity anomaly, the seawater is attracted to the area, and this forms a bulge in the sea-surface. Over negative gravity anomalies, the surface is slightly depressed. Satellite radar measurements of the ocean surface height reveal variations in g, and thus density variations in the upper mantle. There are numerous corrections that have to be applied to the height data obtained by the satellite in order to allow for local disturbances in the height of the sea surface. The fact that the ocean floor sinks as it moves away from the ridges also has to be allowed for. Even when all these corrections are taken into account, a consistent picture of variations in g remains.

The results were quite a surprise. It turned out that there is *not necessarily* a direct correlation between constructive margins and upwelling convection currents, nor between destructive margins and downgoing convection currents. The ocean ridges are clearly locations at which major loss of the Earth's internal heat is taking place, as indeed are the volcanic parts of destructive margins, but there are also areas beneath the deep ocean floors where McKenzie's methods reveal upwelling convection without major release of heat to the surface. On Figure 53, you can see that a region of the Pacific plate that lies away from a constructive margin, still reveals evidence of convective movement in underlying mantle.

So the current view is that convection, in the sense of mass movement of hot material up and cold material down, is occurring on two scales:

1 On the larger scale, the movement of the plates themselves is a convective system. The lithospheric plates are formed by uprise of hot material at constructive margins. At destructive margins, the plates are descending back into the mantle to a depth of at least 700 km. This large-scale uprise

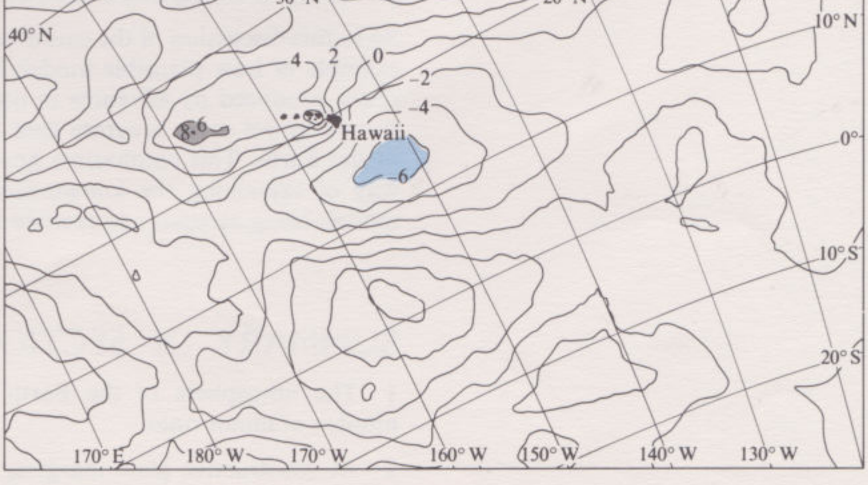


FIGURE 53 Variations in the height of the sea surface, measured by satellite radar altimeters, in the vicinity of Hawaii, in the Pacific Ocean. Positive height variations coincide with positive anomalies, revealing upwelling convection currents in the underlying mantle.

MANTLE PLUME

RIDGE-PUSH FORCE

SINKER EFFECT

followed by a sideways movement and then descent must be completed by a sideways return flow at depth in the asthenosphere, though we can only speculate about the thickness and speed of the return flow.

2 Superimposed on this large-scale circulation is a system of up-currents (often referred to as **mantle plumes**) and down-currents.

These two convection systems interact, so that the bulge caused by the mantle plumes is stretched out by the larger-scale motion of the lithospheric plate. This can be seen on Figure 53, which is drawn so that the motion of the plate is from right to left relative to the plume. The sea-surface height anomalies are distinctly elongated across the diagram.

McKenzie's discoveries leave us still looking for a mechanism for driving plate motions. However, most accounts of plate tectonics had always suggested that several factors could contribute to plate movement. An alternative or supplementary mechanism to mantle convection is known as the **ridge-push force**. You will recall from our discussion of Earth patterns in Section 2 that the ocean ridges are higher than the rest of the ocean basins. It seems that the plates may well be sliding sideways under the influence of gravity off the raised ocean ridges, just as slabs of snow slide off a roof during a thaw, but on a rather grander scale and extremely slowly indeed (Figure 54).

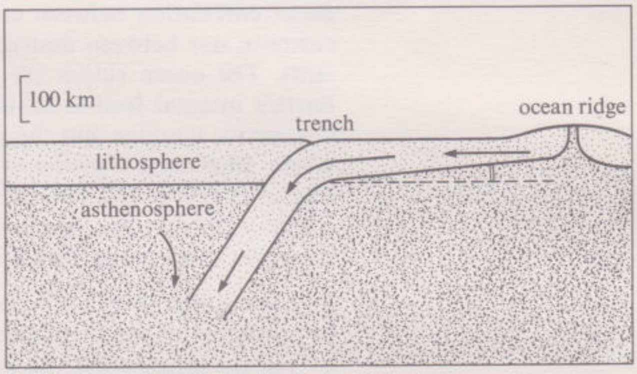


FIGURE 54 A gradient of 1 in 3000 could be enough to cause lithospheric plates to slide downhill, off the raised asthenosphere, beneath ocean ridges.

Another process, in addition to the ridge-push force, is likely to be at work. At subduction zones, the subducted slab starts cool and dense, and as it descends it is compressed still further and becomes still denser. Consequently, this dense inclined slab is sinking under its own weight, and at most is only being helped on its way by downgoing mantle convection. This is called the **sinker effect**.

So in this discussion of the causes of plate motion, we have seen yet another example of how plausible models have been proposed to account for evidence produced by advances in observational techniques, only to be overturned by yet more accurate data obtained by advances in our knowledge of the Earth. This emphasizes how each scientific model affords only one way of explaining the known facts. New data can lead to entirely new models being necessary to provide reasonable explanations.

SUMMARY OF SECTION 5

1 The lithosphere of the Earth consists of seven major plates and a number of minor ones.

2 At constructive plate margins, plates are added to by the intrusion of basaltic and gabbroic material. This produces layered oceanic crust, with basaltic pillow lavas overlying a basaltic dyke complex. At a deeper level, the basaltic layers overlie the plutonic rock, gabbro, which is layered at the base and itself overlies layered peridotite. The layered peridotite lies immediately on top of unlayered peridotite of the upper mantle. The boundary

between the layered gabbro and the layered peridotite is the Mohorovičić seismic discontinuity.

3 At destructive plate margins, oceanic lithosphere is subducted, and the downgoing slab is heated, partly by friction and partly because it is descending into the hotter upper mantle. Partial melting of both the downgoing slab and the overlying mantle results in vigorous volcanic activity. At ocean/ocean margins, the products of the volcanic activity are essentially basaltic in composition. At ocean/continent margins, the products are intermediate in composition between gabbro and granite, and the volcanic products are known as andesites.

4 At conservative plate margins, lithosphere is neither created nor destroyed. Instead, plates move past each other along transform faults. These margins are of present-day importance where they cause shallow earthquake activity near areas of high population density. They have been of importance in the geological past because of their role in accreting continental fragments, known as terranes, on to larger continental blocks.

5 The movement of plates is not related in an obvious way to simple mantle convection cells. There is a large-scale convective movement of material involving accretion to the lithospheric plates at constructive margins, followed by transport of the plates sideways to destructive margins, where they are subducted into the asthenosphere and thence return at some depth to beneath the ridges again.

6 Superimposed on the large-scale motion are a number of smaller scale convection cells in the asthenosphere, which can be identified in oceanic areas by gravity anomalies over 500 km across. The gravity anomalies are positive over the ascending mantle plumes, and negative over the areas of descending material.

7 In addition to the convective processes in the asthenosphere, there are other processes operating which promote plate motion. The plates may be sliding off the uplifted asthenosphere beneath the ocean ridges, an effect known (somewhat misleadingly) as the ridge-push force. At subduction zones, the subducted lithospheric slab is compressed to a density at which it can sink under its own weight; this is called the sinker effect.

6 A REVOLUTION IN THE EARTH SCIENCES

We cannot conclude the plate tectonic story without considering a model of a different kind, that is a model to describe how major scientific advances take place. If you had ever thought about this before starting this Course, you might well have constructed a model in which scientific advances take place by researchers diligently chipping away at a vast block of hitherto unknown facts and laws. Furthermore, you may also have thought that scientists amass vast amounts of data, and then produce generalizations from these. After reading the preceding account of the development of plate tectonics, you should have begun to realize that science is not as straightforward, or as boring, as this.

In 1962, at the same time as the major developments in the Earth sciences were taking place, a historian of science, Thomas Kuhn, published a classic book, *The Structure of Scientific Revolutions*, which suggested an alternative to the standard view that science progresses by the gradual accumulation of new facts and formulation of new theories. Kuhn suggested that many major advances in science take place via revolutions, which are preceded by a period that he called 'normal' science and signalled by a period of 'extraordinary' science.

He likened 'normal' science to puzzle-solving; it is research firmly based on past scientific achievements that are generally acknowledged as supplying the foundation on which new work can be based. However, there may come

a time when researchers divide into different schools of thought, and a period of uncertainty, or 'crisis', ensues. 'Extra-ordinary' science begins when one of these competing ideas takes over ('breakthrough'), because it enables a whole range of previously puzzling phenomena to be satisfactorily explained.

This complete change, or revolution, in attitudes and beliefs, is followed by a 'mopping-up' phase, during which existing and new data are re-interpreted. Such 'mopping-up' operations, according to Kuhn, are what engage most scientists throughout their careers and constitute 'normal' science.

Since 1962, Kuhn's view of science has often been compared with that of Sir Karl Popper, which was discussed in the Introduction to Unit 1. On continental drift, Popper would argue that Wegener's ideas opened up a possible avenue of scientific advance because one could compare the predictions of Wegener's theory with those derived from currently accepted ideas. It then became a question of deciding which lines of investigation would yield observations that would clearly support or contradict the various theories. According to this view, the fitting of continental margins using computers, the determination of apparent polar wandering curves, and the establishment of magnetic anomaly patterns are 'experiments' (investigations), the results of which progressively amounted to the falsification of the theories competing with the theory of continental drift. Kuhn, on the other hand, would argue that this emphasis on falsification oversimplifies the nature of the revolution in the Earth sciences: he believes that a correct description must include social and psychological influences as well.

6.1 THE REACTION TO WEGENER (TAPE SEQUENCE)

Do you think developments in the Earth sciences during this century fit Kuhn's revolutionary model? Think back over what you have studied in these two Units; Table 5 should help you do this. Listen also to the tape sequence 'The reaction to Wegener' (Tape 2, Side 1, Band 2). During the sequence, four scientists comment on the reactions to Wegener's ideas on continental drift, and why it took so long for the new view of the Earth—plate tectonics—to emerge.

The background and research interests of the four speakers are as follows:

Professor Sir Edward Bullard, FRS, was head of the Department of Geodesy and Geophysics at the University of Cambridge in the early 1960s, when continental drift became a generally acceptable hypothesis. He worked on ocean heat-flow measurements in the 1950s (see Section 4.5), and collaborated in the preparation of the computer-fit map of the continents bordering the Atlantic (see Figure 19).

Professor Warren S. Carey is an Australian and, like many southern-hemisphere geologists, was convinced of the validity of the drift hypothesis long before most geologists in the northern hemisphere. In the 1950s he proposed that many oceans had opened by rotation of the continents caused by expansion of the Earth. He still believes, unlike most geologists, in an expanding Earth, and considers that plate tectonics does not provide a completely satisfactory explanation for the geology of the crust.

Professor Keith Runcorn, FRS, was one of the pioneers of palaeomagnetism, having recognized that differences in polar-wandering curves could only be reconciled by invoking continental drift.

Professor Fred Vine, FRS, with *Dr Drummond Matthews*, linked the magnetic reversal time-scale deduced from continental rocks to oceanic magnetic anomaly patterns (see Section 4.7).

TABLE 5 Some key events and contributions in the development of the plate-tectonic theory

	Key developments	Participants mentioned in these Units (or earlier Units)
Late 19th and early 20th century	Ideas on Earth history dominated by the idea that the Earth was cooling down from an original molten state	
1896	Discovery of radioactivity	
1911	First summary of radioactive dates of rocks published	Holmes
1915	First edition of *The Origin of the Continents and Oceans*	Wegener
1920s	Several major debates on continental drift; most workers anti-drift, with only geologists in southern hemisphere generally favouring the idea	Du Toit
1931	Publication of paper proposing that continental drift is driven by convection currents in the mantle powered by heat from radioactive minerals	Holmes
Late 1950s	Ocean exploration: discovery of East Pacific Ridge, median rift valleys of ocean ridges; relative youthfulness of seamounts; heat-flow studies	Hess, Bullard
	Palaeomagnetic data supports drift theory	Blackett, Runcorn
	Inclined zones of earthquakes around Pacific measured	Wadati, Benioff
1960, 1962	Geopoetry; sea-floor spreading described first, named later	Hess, Dietz
1963	First magnetic reversal time-table proposed	Cox and others (Units 5–6)
	Magnetic anomaly pattern over ocean ridges related to magnetic reversals and sea-floor spreading	Vine and Matthews
	Two leading journals reject paper relating oceanic magnetic anomaly patterns to reversals and spreading	Morley
1965 onwards	Mass of evidence described supporting Vine–Matthews hypothesis	
1965	Transform-fault concept proposed	Wilson
1967/68	New global tectonics proposed and 'verified'	Morgan; Le Pichon: Isacks, Oliver and Sykes; McKenzie and Parker
1968	Deep-Sea Drilling Project confirms, by sampling, age of S. Atlantic Ocean floor predicted by Vine–Matthews hypothesis	

SUMMARY OF SECTION 6

There are three lessons to be learnt from this brief diversion into the history of science. One is that progress in science does not appear to take place at a gradual and constant pace. The second is that individuals make their mark on science by a combination of diligence, imagination—and good fortune. And the third lesson is that a revolutionary idea that appears to be indisputable to one generation of scientists may be toppled by the next—witness what happened to late nineteenth-century ideas of a contracting Earth less than 100 million years old!

Now see if you can answer SAQs 15–19. Write about 100 words for each answer.

SAQ 15 What was the generally accepted view concerning the origin of the Earth and its major surface features at the turn of the century?

SAQ 16 What evidence is there that the Earth sciences went through a period of uncertainty concerning the origin of continents and oceans?

SAQ 17 When do you consider that the revolution in the Earth sciences occurred?

SAQ 18 Why do you think Wegener failed to convince geologists of the validity of the continental drift hypothesis? What evidence did he lack that became available later to convince sceptics?

SAQ 19 What technological and political developments influenced the collection of new evidence in favour of continental drift, and the later hypotheses of sea-floor spreading and plate tectonics?

OBJECTIVES FOR UNITS 7–8

After you have worked through these Units, you should be able to:

1 Explain the meaning of, and use correctly, all the terms flagged in the text.

2 Explain why the continued existence of continents for at least three thousand million years implies a mobile outer part of the Earth. (*SAQ 3*)

3 Describe the difference between the non-specialist's concept of oceans and continents and that understood by Earth scientists. (*SAQ 4*)

4 Describe the major patterns shown by the Earth's relief features, ages of continental and oceanic rocks, and the distribution of seismic and volcanic activity. (*SAQ 5*)

5 Correctly list, or recognize from given examples, the major lines of evidence that support the continental drift hypothesis. (*SAQ 6*)

6 Demonstrate your understanding of the concepts of isostasy and gravity anomalies by interpreting given data concerning actual and hypothetical crustal models. (*ITQ 1 and SAQ 7*)

7 Demonstrate your understanding of the hypothesis of sea-floor spreading by summarizing the evidence that supports it, and by carrying out calculations based on sea-floor magnetic anomaly data. (*SAQs 8–11*)

8 Describe the plate tectonic hypothesis. (*SAQ 12*)

9 Describe the evidence that favours the plate tectonic hypothesis. (*SAQ 13*)

10 Draw on a map of the world the location of the seven major lithospheric plates, and indicate whether their boundaries are constructive, conservative or destructive. (*ITQ 10*)

11 Distinguish constructive, conservative and destructive plate margins on the basis of the rock types they contain, their structures and their geophysical characters. (*ITQ 11 and SAQ 14*)

12 Outline events in the revolution in Earth sciences in terms of periods of 'normal science', 'crisis', 'breakthrough', and 'mopping-up'. (*SAQs 15–17*)

13 Explain why Wegener's concept of continental drift took more than 50 years to become generally accepted by Earth scientists. (*SAQ 18*)

14 Summarize the technological and political developments that contributed to the formulation of the revolution in the Earth sciences. (*SAQ 19*)

ITQ ANSWERS AND COMMENTS

ITQ 1 The Scandinavian region is characterized by a negative gravity anomaly, because the crust has not yet risen enough to compensate fully for the weight of ice that has melted. Therefore there is a mass deficiency beneath this region.

ITQ 2 Wadati–Benioff zones occur beneath regions of *explosive* volcanic activity; you should already be familiar with the association of such activity inland from trenches.

ITQ 3 The revised rate of movement on one limb of the convection cell is approximately 2.3 cm yr^{-1} (that is, an opening of 5000 km in 110 Ma, which is a total opening rate of approximately 4.6 cm yr^{-1} or 2.3 cm yr^{-1} on one limb of a convection cell).

ITQ 4 Evidence in favour of upwelling convection currents underlying ocean ridges includes:

(a) high heat-flow values in these regions (see Figure 27);

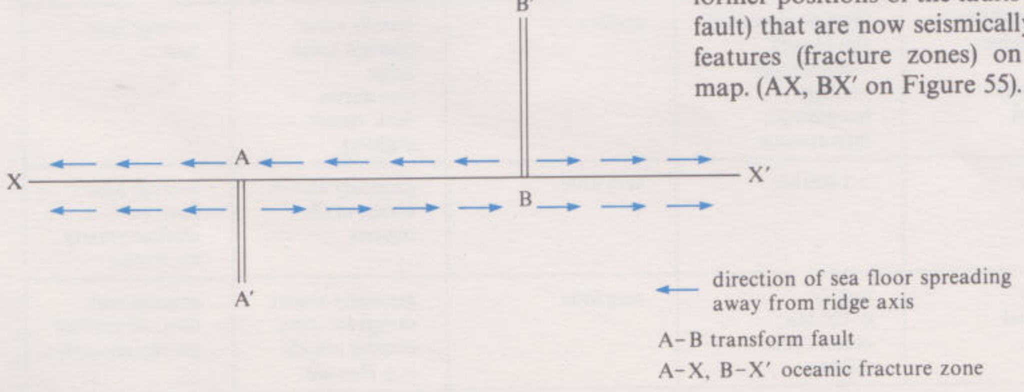
(b) active volcanism and seismicity along ocean ridges (see Figures 9 and 10);

(c) the fact that ridges are topographic 'highs' rising above the general level of the ocean basins suggests that they are less dense regions; this lowered density is due to expansion caused by higher temperatures.

ITQ 5 If Hess's speculation that oceans are replaced by new mantle material every 300 to 400 Ma is correct, then there should be no rocks older than this on the ocean floors. When he wrote his paper, Hess knew that rocks no older than about 120 Ma had been found in the oceans, and so used this as evidence in favour of his hypothesis. More recent work, as you will see, has extended this figure to 190 Ma, so it seems that Hess's figure of 300 to 400 Ma was an over-estimate.

ITQ 6 Wegener envisaged the continents floating on the mantle (although he did not use the term mantle) to be like ice-floes floating on water. So Hess's concept was completely different—to him oceanic and continental crust behaved as *one* slab forming the outer part of a convection cell.

FIGURE 55 An annotated version of Figure 39, for use with the answer to ITQ 9.



ITQ 7 (a) The leading edges of continents 'are strongly deformed ...' Mountain belts ringing the Pacific are examples of such deformation.

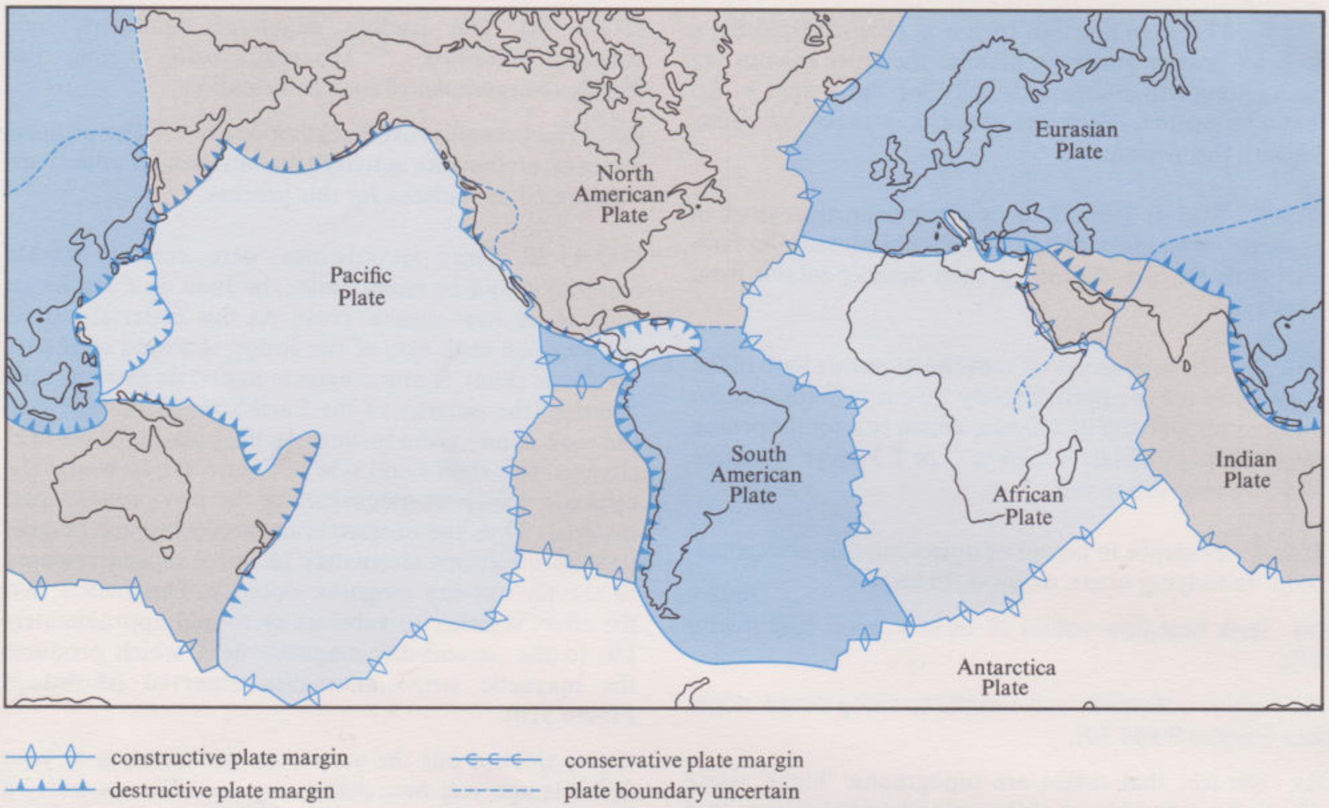
(b) 'The oceanic crust, buckling down ...' The inclined zones of earthquake activity (Wadati–Benioff zones) are interpreted as evidence for this process.

ITQ 8 If Hess's speculations were correct, mantle material would be rising under the Juan de Fuca Ridge to produce new oceanic crust. As this material moved sideways on each side of the Ridge, it would cool past the Curie point of any magnetic materials present, thus 'freezing' the polarity of the Earth's magnetic field into the rock at any given instant. As the polarity of the field changed (see right-hand side of Figure 33), so would the resultant remanent magnetism of the new oceanic crust material. Thus the oceanic crust would become magnetized in directions alternately identical to and opposed to the present-day magnetic polarity. This means that the effect is either to subtract or to add approximately 1% to the present-day magnetic field, which produces the magnetic stripe anomalies observed (shown in Figure 31b).

If you worked out the answer to this question at your first attempt, you were doing very well! Do not worry if you had difficulty in understanding this explanation; the next part of the text and the TV programme will explain it in more detail. You may have been surprised that the authors of the 1961 paper that described the magnetic anomaly patterns in the Eastern Pacific did not propose this explanation. They did not do so for two reasons. First, at the time they did not have access to data concerning the detailed relief of the region, because they were still held as top secret by the US Coast and Geodetic Survey (the relief of the Juan de Fuca Ridge identified on Figure 31b was revealed at a later date when the information was published). Second, Hess's 'essay in geopoetry' was not formally published until 1962, although it had been widely circulated in pre-print form before that time.

ITQ 9 Figure 55 is an annotated version of Figure 39, showing that slippage of one block of oceanic crust past another *only occurs between points A and B*. To the left of A, both segments of crust are spreading away from the ridge (A–A′, B–B′) at the same rate, and the same situation applies to the right of B. The fault between A and B is known as a *transform fault*. Traces of the former positions of the faults (or, strictly, one side of the fault) that are now seismically inactive show up as relief features (fracture zones) on the World Ocean Floor map. (AX, BX′ on Figure 55).

ITQ 10 FIGURE 56 The answer to ITQ 10.



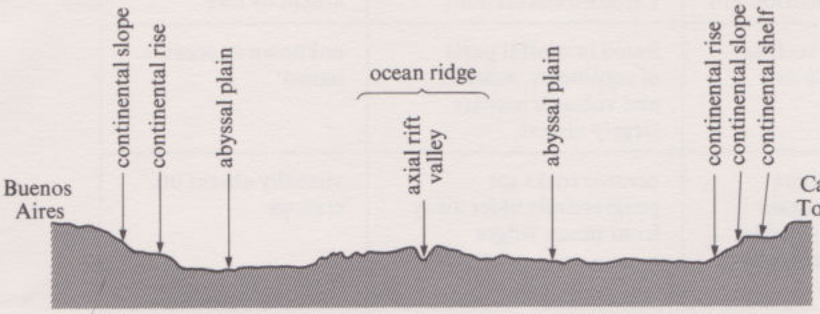
ITQ 11 Your completed Table 4 should look like Table 6.

TABLE 6

	Relief	Age of rocks (0–10 Ma, 10–100 Ma, or >1 000 Ma)	Seismic activity (shallow, intermediate or deep focus)	Volcanic activity (effusive or explosive)	Other notable features, such as heat flow (high, average, low) or gravity anomalies
Constructive plate margins	ocean ridge with median rift valley, and rugged relief	0–10 Ma	shallow	effusive	high heat flow
Destructive plate margins Ocean/ocean	trench/island arc	mostly 10–100 Ma	Wadati–Benioff zone	explosive	low heat flow in trench; negative gravity anomaly over trench
Ocean/continent	trench; mountain belt	mostly 0–100 Ma; older on continental side	Wadati–Benioff zone	explosive	low heat flow in trench; negative gravity anomaly over trench
Continent/continent	mountain belt	very variable	shallow and intermediate focus	usually absent	average heat flow
Conservative plate margins	Oceanic: offsets in oceanic ridge crests Continental: no special features	Oceanic: less than 100 Ma old Continental: variable but younger than cratons	shallow	usually none (though some ridge transforms 'leak' basalt slightly)	average heat flow
Mid-plate regions Continental	relatively flat cratons	>1 000 Ma	very little	generally absent, except in rift regions	average heat flow; no marked gravity anomalies
Oceanic	relatively flat abyssal plains	mostly 0–100 Ma; oldest about 190 Ma	very little	generally absent, except for some oceanic islands (e.g. Hawaii)	average heat flow; no marked gravity anomalies

SAQ ANSWERS AND COMMENTS

SAQ 1 FIGURE 57 The answer to SAQ 1.



SAQ 2 Your completed Table 2 should look like Table 7.

TABLE 7

	Relief	Age of rocks	Seismic activity	Volcanic activity
Continental features Cratons	0–3 km, relatively flat	old > 1 000 Ma	virtually absent	none
Young mountain belts not bordering oceans	rugged, 3–8 km	generally less than 60 Ma, trending E-W from Mediterranean to Tibet and China	very active; mostly shallow, but deeper foci in Mediterranean region	rare; except in Mediterranean area, where there is explosive activity
Young mountain belts bordering oceans	rugged, 3–6 km	Rockies: 100–200 Ma; Andes younger	very active; shallow on ocean side, becoming deeper inland (Wadati–Benioff zones)	very active; explosive in nature
Oceanic features Ocean-basin floors	3–5 km below sea-level; flat and smooth	60 to about 190 Ma	very little	very little, except for a few volcanic islands with effusive activity
Ocean ridges	2–5 km above ocean basin floors, relatively rugged, traversed by fractures, and some ridges have central rift valley	very young; youngest rocks (0–10 Ma) occur here	active; shallow foci only	active; effusive
Ocean trenches	up to 11 km below sea-level, 5 km below ocean basin floors	relatively young and variable (not discussed so far in the text)	active; associated with zones of shallow, intermediate and deep-focus earthquakes	associated island arcs or mountain belts have explosive volcanic activity

SAQ 3 The existence of continents as discrete slabs dotted about the globe suggests that some process must have operated to segregate the lighter granitic crust of which they are composed. This, coupled with the existence of continents and mountain belts for 3 000 Ma despite continued erosion, suggests processes operating within the Earth that continually 'renew' the continents.

SAQ 4 To the non-specialist, the 'ocean' is an area of the Earth covered by the sea, whereas the 'continent' is dry land. To geologists the wet–dry distinction has little significance; what is more important to them is the fact that the Earth has two 'preferred levels' as shown by the frequency distribution plot in Figure 5. Seismic studies show that these two levels are underlain by crust of different densities, the higher level (the continental platform) being floored by less dense crust than that beneath the lower one. The boundary between continental and oceanic crust is probably marked by the central steeper part of the cumulative frequency curve (the continental slope).

SAQ 5 Your completed Table 3 should look like Table 8.

TABLE 8

	Geographical distribution	Patterns/associations	Regions where absent or rare
Rocks older than 1 000 Ma	only in cratons such as Baltic, Canadian and African shields	found in central parts of continents; seismic and volcanic activity largely absent	unknown in ocean basins
Rocks younger than 100 Ma	bulk of ocean floors of this age; mountain belts of circum-Pacific and Alpine Himalayan Belts	oceanic rocks get progressively older away from ocean ridges	virtually absent on cratons
Effusive volcanic activity	along central parts of oceanic ridges, on African craton, and scattered within ocean basins away from trenches	equidistant between bordering continents in Atlantic Ocean; linked with shallow-focus seismic activity	on cratons, and largely absent from young mountain belts
Explosive volcanic activity	circum-Pacific ring of fire	usually associated with ocean trenches and earthquakes at all depths	central part of ocean basins, most cratons
Zones of shallow-focus earthquakes	circum-Pacific belts, Alpine Himalayan Belt and ocean ridges	associated with effusive volcanism along ocean ridges, explosive volcanism along mountain belts and island arcs	cratons, ocean basin floors
Zones of intermediate- and deep-focus earthquakes	circum-Pacific belt	get deeper in direction outward from central Pacific; associated with explosive volcanic activity	cratons, ocean basins

SAQ 6 The four major lines of evidence that support the continental drift hypothesis are:

1 relief of continents;

2 match of ancient mountain belts between continents;

3 palaeoclimatic evidence;

4 similarities between fossils found on now-separated continents.

SAQ 7 In Figure 26, woodblocks (a) and (c) are depressed lower than block (b), and so are characterized by negative gravity anomalies, with (c) having the larger of the two. Blocks (d) and (e) are higher in the water than (b) and so are the sites of positive gravity anomalies, with (d) the larger of the two.

SAQ 8 At 1 400 km out from the ocean ridge, the ocean floor is interpreted to be 77 Ma old, that is, the spreading rate on one limb = 1 400 km/77 Ma $\approx 1.8\,\text{cm yr}^{-1}$.

SAQ 9 The 10 Ma anomaly can be traced through to the 350 km location as shown on Figure 58.

SAQ 10 The spreading rate is $3.5\,\text{cm yr}^{-1}$ ($350\,\text{km}/10^7\,\text{yr}$) from 0–10 Ma.

SAQ 11 Again, you need to trace the 30 Ma 'marker' through from the South Atlantic, as shown on Figure 58. The 10 Ma age was located in SAQ 9 at 350 km; the 30 Ma point is 700 km out from the ridge crest, so, in the period between 10 and 30 Ma ago, 350 km of ocean floor was formed. Therefore the spreading rate was $1.75\,\text{cm yr}^{-1}$, slower than the following 10 Ma period (at $3.5\,\text{cm yr}^{-1}$).

SAQ 12 You should have completed the blanks in the description of plate tectonics as follows:

Ocean floor is envisaged as continuously accreting to a *rigid* (a) plate which is *seismically* (b) inactive, and which interacts with other plates along active zones of *volcanism* (c) and seismicity. The movement of the plates over the surface of a *sphere* (d) can be described with reference to a *pole* (e) of rotation. *Transform* (f) faults trend along the direction of *small* (g) circles about the *pole* (e) of rotation, whereas ocean ridges between these faults trend along *great* (h) circles passing through the *poles* (e).

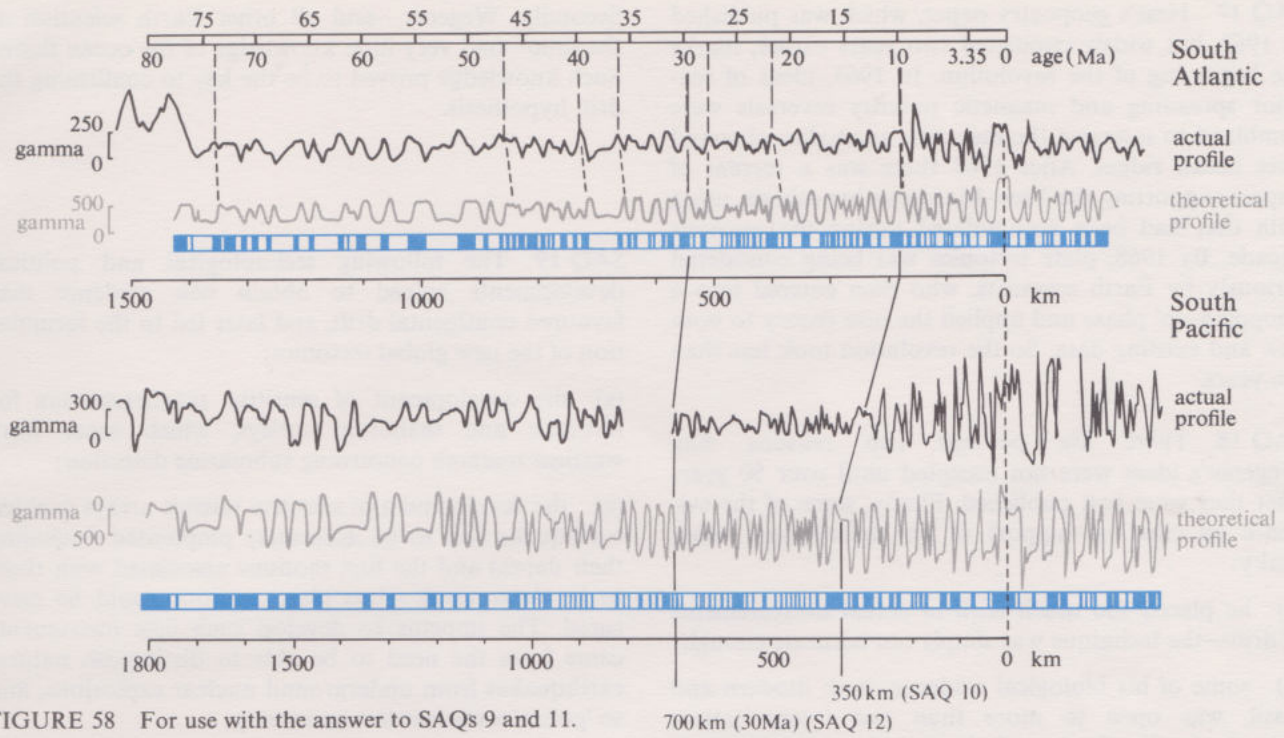


FIGURE 58 For use with the answer to SAQs 9 and 11.

SAQ 13

1 B, C, E. Palaeoclimatic and palaeomagnetic data contributed to the confirmation of the continental drift hypothesis, as did the computer fitting of the relief of continental margins.

2 Items A and D (deep-sea drilling and ocean-floor magnetic anomalies) confirmed the sea-floor spreading hypothesis, which is a corollary of drift. So you might have been tempted to choose these two under (1). You should have also chosen G, the magnetic polarity reversal timetable.

3 The concept of transform faults was confirmed by detailed studies of magnetic anomaly patterns (D), and so the formulation of the magnetic polarity reversal timetable is also relevant (G), but most of all by studies of earthquakes along the lines of oceanic fracture zones (F).

4 It could be said that all the items support the idea of plate tectonics. But earthquake studies (F) provide direct evidence concerning the *directions of movement* of the crustal plates at the present time.

SAQ 15

At the turn of the century, most geologists believed that the Earth was still cooling down after its birth as a molten ball from the Sun. This implied that it was contracting, which would mean that continents were more likely to be coming together rather than drifting apart. In addition, researchers were wary of any ideas that smacked of catastrophism; they were content to interpret the Earth's features in terms of processes that could be observed in action at the present time.

SAQ 16

The publication of Wegener's book in 1915 signalled the start of a period of uncertainty about the origin of continents and oceans, which hitherto had been largely thought of in terms of vertical, rather than horizontal, movements. But until the late 1950s the majority of geologists were not disciples of Wegener. Only when palaeomagnetic results gave the geophysicists evidence (which they had collected) that continents wandered, did they begin to reconsider their belief that the Earth was too rigid for major lateral movements to have occurred in its crust. Thus the real crisis period was in the late 1950s and early 1960s.

SAQ 14

Constructive margins

1	2 ✓	3 ✓	4
5	6	7	8
9	10	11 ✓	12 ✓
13 ✓	14	15	16 ✓

Destructive margins

ocean/ocean (island arc)

1	2 ✓	3	4 ✓
5 ✓	6	7 ✓	8 ✓
9 ✓	10 ✓	11 ✓	12
13	14	15 ✓	16

ocean/continent (Andean)

1	2	3	4 ✓
5	6 ✓	7 ✓	8 ✓
9 ✓	10 ✓	11 ✓	12
13	14	15 ✓	16

SAQ 17 Hess's geopoetry paper, which was published in 1962, but widely circulated two years earlier, marks the beginning of the revolution. In 1963, ideas of sea-floor spreading and magnetic polarity reversals were combined to interpret the magnetic anomalies observed over ocean ridges. After 1968 there was a torrent of papers supporting the Vine–Matthews hypothesis, using data that had been accumulated during the previous decade. By 1968, plate tectonics was being considered seriously by Earth scientists, who then entered into a 'mopping-up' phase and applied the new theory to both new and existing data. So the revolution took less than ten years.

SAQ 18 There are perhaps two reasons why Wegener's ideas were not accepted until over 50 years after they were first published. Firstly, some of the evidence he cited in support of his theory was rather shaky:

(a) he placed too much faith in actual measurements of drift—the technique was simply not accurate enough;

(b) some of his biological evidence, both modern and fossil, was open to more than one interpretation, because the distribution of plants and animals depends on climatic controls as well as links between continents;

(c) he did not present *detailed* evidence or maps to show how the continents once fitted together.

Secondly, Wegener—and all other Earth scientists at the time—had very little knowledge of the ocean floors. Such knowledge proved to be the key to confirming the drift hypothesis.

SAQ 19 The following technological and political developments helped to obtain new evidence that favoured continental drift, and later led to the formulation of the new global tectonics:

(a) the development of sensitive magnetometers for airborne and seaborne surveys, which arose from wartime research concerning submarine detection;

(b) the development of sensitive seismic arrays enabled earthquake foci to be accurately pinpointed (including their depth) and the first motions associated with them to be determined. Thus plate motions could be measured. The impetus to develop such new instruments came from the need to be able to distinguish natural earthquakes from underground nuclear explosions, and so 'police' a nuclear test ban treaty;

(c) techniques of deep-sea drilling owe their initial development to the Mohole project, which for a period during the 'cold war' was seen by the USA as a race to reach the Mohorovičić discontinuity before the USSR.

FURTHER READING

Gass, I. G., Smith, P. J., and Wilson, R. C. L. (eds) (1972) *Understanding the Earth*, 2nd edn., Artemis Press. This book contains a number of chapters that explain in more detail the material considered in Units 7–8 (Chapter 16, Sea-Floor Spreading, by F. J. Vine; Chapter 19, Plate Tectonics, by E. R. Oxburgh.)

Wyllie, P. J. (1976) *The Way the Earth Works*, John Wiley & Sons. An excellent book that covers much the same ground as S102 Units 5 to 8. It also contains a review of arguments against the new global geology.

Geological Museum (1972) *The Story of the Earth*, HMSO. A small, cheap (about £1), lavishly illustrated colour booklet summarizing the 'new geology'.

Smith, D. B. (ed.) (1981) *The Cambridge Encyclopaedia of Earth Sciences*, Cambridge University Press. A well illustrated, fairly comprehensive treatment by leading experts; useful for general reference.

Muir-Wood, R. (1985) *The Dark Side of the Earth*, Unwin-Hyman. This fascinating account of the origin of the concept of plate tectonics and its focal role in the revolution in Earth sciences is now in paperback.

Menard, H. W. (1986) *The Ocean of Truth*, Princeton University Press. A personal history of the critical years in oceanography (1950–1966) and the evolution of the concept of sea-floor spreading.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to the following sources for material used in these Units:

Figures 2a, 16a, 47c (left) and 49e National Environmental Research Council by permission of the Director of the Institute of Geological Sciences; *Figures 2b and c and 3a* Aerofilms; *Figure 3b* NASA; *Figure 17* J. C. Holden; *Figures 18a and b* from A. Holmes (1931) *Trans. Geol. Soc. Glasg.*, Vol. 18; *Figure 18c* from A. L. Du Toit (1937) *Our Wandering Continents*, Oliver & Boyd; *Figures 19, 38 and 45* from P. J. Wyllie (1976) *The Way the Earth Works*, John Wiley; *Figure 20* E. Bullard; *Figure 21* from B. C. Heezen, 'Deep-sea Floor' in S. K. Runcorn (ed.) (1962) *Continental Drift*, Academic Press; *Figures 22a and b* from M. N. Hill (ed.) (1962) *The Sea*, Vol. 3, John Wiley; *Figure 26* from A. N. Strahler (1963) *The Earth Sciences*, Harper and Row; *Figure 27* from A. E. Maxwell (ed.) (1970) *The Sea*, Vol. 4, Wiley-Interscience, by permission of A. E. Langseth; *Figure 30a*, Geological Survey of Great Britain. Crown Copyright; *Figure 30b* US Coast and Geodetic Survey; *Figure 31* Geological Society of America; *Figure 34b* from F. J. Vine and D. H. Matthews (1963) 'Magnetic anomalies over ocean ridges' in *Nature*, Vol. 199, Macmillan; *Figure 35 a–d* from F. J. Vine, 'Magnetic anomalies associated with mid-ocean ridges', pp. 73–89 in R. A. Phinney (ed.) (1968) *The History of the Earth's Crust*, Princeton University Press; *Figure 35e* from J. R. Heirtzler (1968) 'Sea-floor spreading' in *Scientific American*, copyright © 1968 Scientific American Inc. All rights reserved; *Figures 36, 41, 42 and 58* from I. Gass *et al.* (1972) *Understanding the Earth*, 2nd edn, Artemis Press; *Figure 37a* Scripps Institution of Oceanography; *Figure 37b* National Science Foundation; *Figures 47a, 49b and c* from The Geological Museum (1973) *The Story of the Earth*. Reproduced by permission of the Controller of HMSO; *Figure 47c (right)* from W. S. Broecker (1974) *Chemical Oceanography*, Harcourt, Brace, Jovanovich Inc., and by permission of C. D. Hollister, Woods Hole Oceanographic Institute; *Figure 49d* Peter Francis.

INDEX FOR UNITS 7 AND 8

PLATE 1 Till deposit (also known as boulder clay) laid down beneath melting ice, Durham. The hammer handle is about 35 cm long.

PLATE 2 Open-cast coal site, Durham.

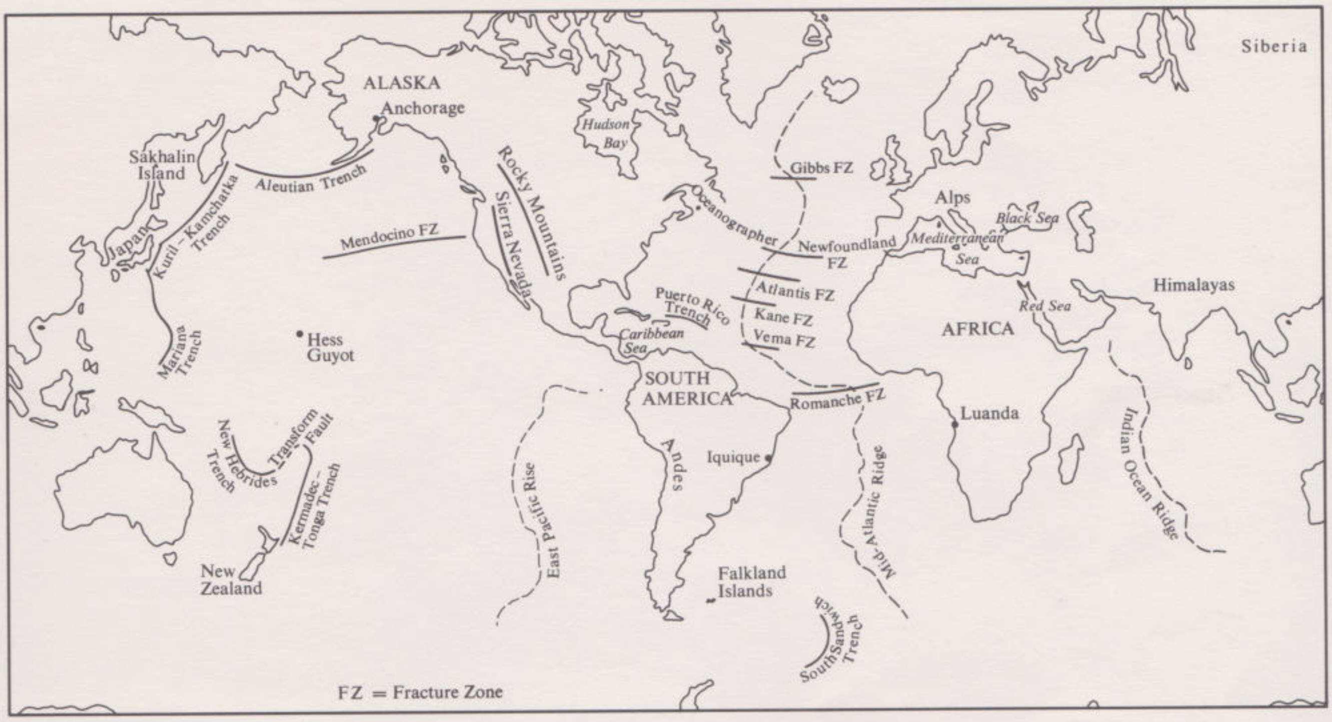
PLATE 3 Plant remains (fossils) of vegetation typical of the swampy forest deposits that after compaction formed coal seams.

PLATE 4 Map showing the present-day distribution of climatic/vegetation zones.

Key
dark green — tropical forest
light green — savannah grassland
light brown — desert
dark brown — other cooler climates
white — arctic

PLATE 5 Dune-bedding preserved in sandstone, Durham.

KEY to World Ocean Floor map



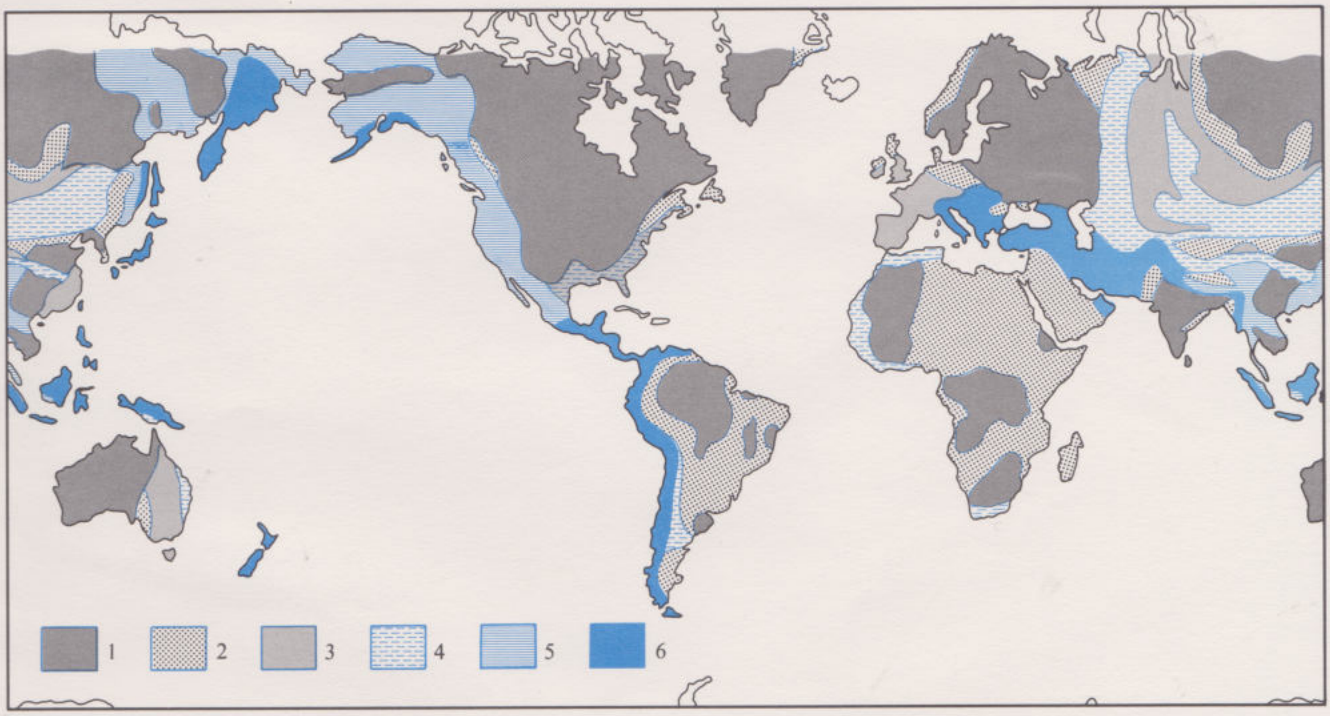


FIGURE 7 Map showing the distribution of ages of rocks on the continents formed during past phases of mountain building. The way in which rocks can be dated will be discussed in detail in Units 28–29.

1 Rocks formed more than 1 000 Ma ago: these regions, termed *cratons*, have remained unaffected by earth movements for a considerable period, and they form the stable 'nuclei' of the continents (AV sequence 'Crustal patterns'). Such regions exhibit a relatively subdued relief in contrast to the rugged relief associated with 'young' mountain belts such as the Alps, Andes, Himalayas and Rockies (see 5 and 6 below).

2 Rocks formed 1 000–600 Ma ago;

3 Rocks formed 600–400 Ma ago;

4 Rocks formed 350–250 Ma ago;

5 Rocks formed 200–100 Ma ago;

6 Rocks formed 60 Ma ago to the present.

You will see from the above intervals of rocks that there were gaps between the main phases of mountain-building.

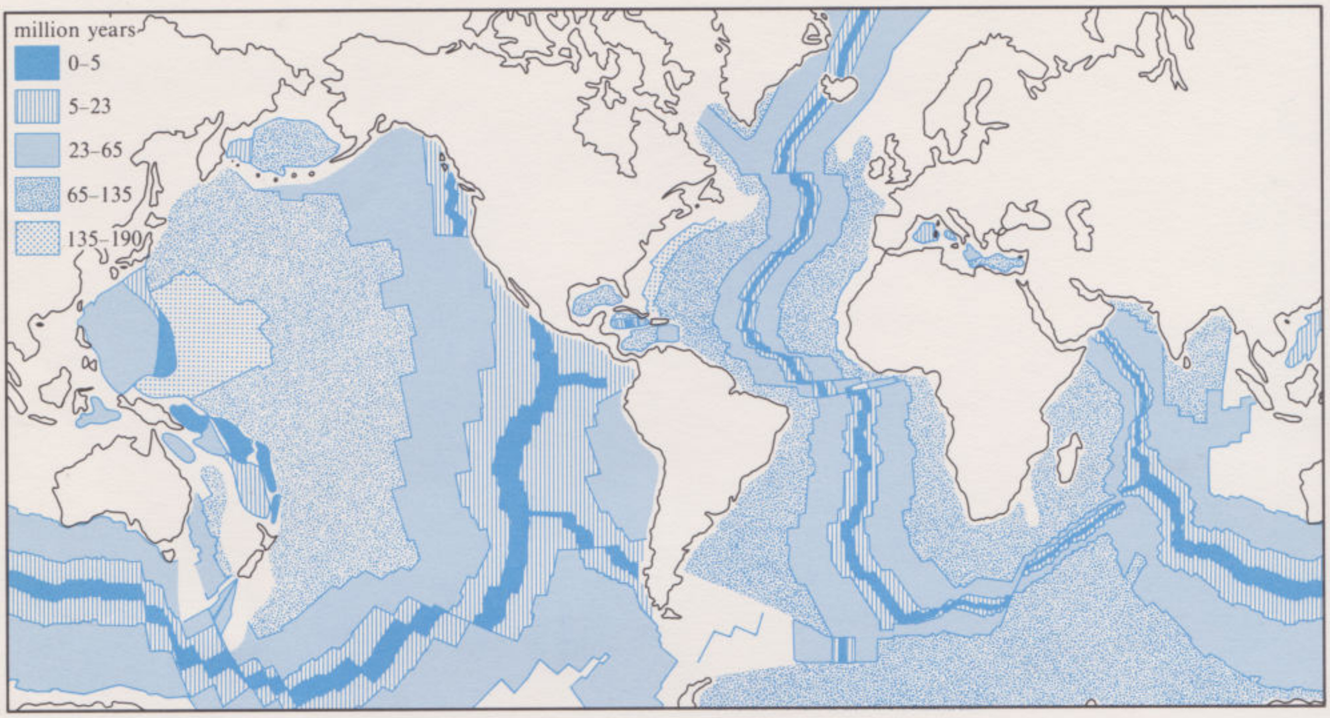


FIGURE 8 Map showing the age of the ocean basins, as determined by studies of magnetic anomalies. Blank areas are those in which there are insufficient data to support the interpretation of ocean floor ages. The magnetic anomaly interpretation method is described on pages 40–45.

FIGURE 9 Map showing the distribution of active volcanoes. Black dots show the occurrence of effusive volcanoes, whose activity is dominated by outpourings of liquid lava (see specimen S3 in your Experiment Kit). Blue dots signify explosive activity, produced by the release of large amounts of gas as the lava nears the vent of the volcano: the resultant rock types include volcanic ash and lava containing abundant gas bubbles (see specimen S2 in your Experiment Kit). The AV sequence 'Igneous rock formation' (associated with Units 5–6) described these two types of activity in more detail.

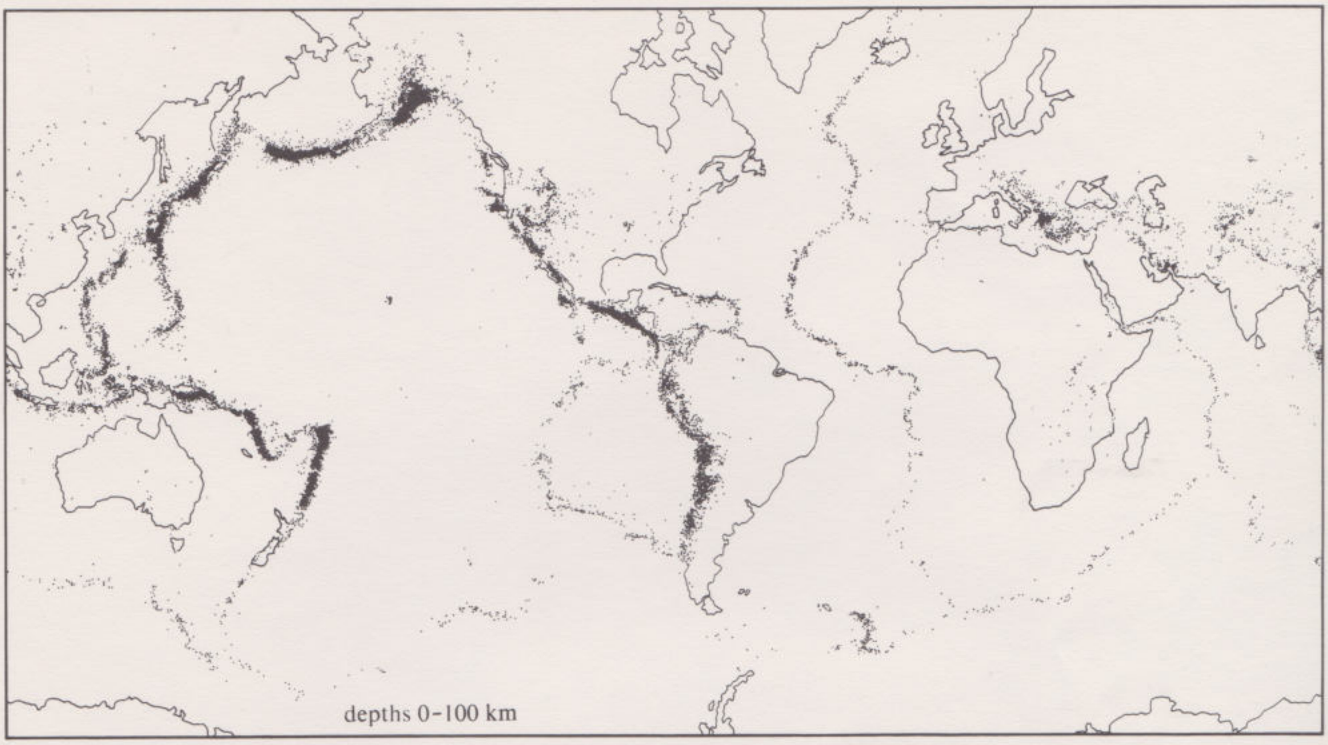


FIGURE 10 Map showing the distribution of all shallow (less than 100 km depth) earthquake foci recorded between 1961 and 1987.

FIGURE 11 Map showing the distribution of all intermediate-focus (100–300 km depth; black dots) and deep-focus (300–700 km depth; blue dots) earthquakes recorded between 1961 and 1987.